FATIGUE STUDIES OF 24S-T AND 24S-T ALCLAD SHEET WITH VARIOUS SURFACE CONDITIONS

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SUMMARY

Fatigue studies of two common structural aircraft materials, 24S-T and 24S-T Alclad, with respect to various surface conditions are presented in this investigation. Only one gage of the two materials, 0.040 inch, was used throughout the investigation. Various abrasives, crocus cloth, numbers 240, 180 and 100 Aloxite Finishing Cloth, and number 60 sandpaper were used to impart scratches of different depths to the surfaces of the specimens.

From the fatigue results obtained average stress concentration factors resulting from each scratch pattern imparted by the various abrasives were calculated. The repeated flexure fatigue strengths of the alloys for surfaces scratched with the several abrasives are presented and also the curves of the relation between the average depths of scratch and concentration factor for repeated flexure fatigue are included.

INTRODUCTION

Even though the various components of aircraft are designed to withstand certain calculated loads, the limits of which are assumed never to be exceeded in the normal specified operation of the aircraft, failures of these components may occur due to fatigue. These fatigue failures may be brought on by any number of reasons, one of the major causes with respect to sheet components being scratched surfaces, as a result of handling and fabrication.

Surface scratches and varying degrees of finish have been of great concern to designers and a great deal of work has been carried out in this respect on various steels. However, the available fatigue data on present day aluminum alloys is indeed meager. It has been shown in numerous tests by Horger[1], Hankins[2], Lea[3], Moore and Kommers[4], Thomas[5] and a number of other investigators that surface scratches are very deleterious to the endurance strength of various steels. Matthaes[6] has shown by tests made on an early aluminum alloy

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[1]O. J. Horger, "Fatigue Strength of Members Influenced by Surface Conditions," Product Engineering, 11:490, December 1940.

[2]G. A. Hankins, M. L. Becker and H. R. Mills, "Further Experiments on the Effect of Surface Conditions on the Fatigue Resistance of Steels," Journal of the Iron and Steel Institute, 133:399-425, February 1936.

[3]F. C. Lea, "Effect of Discontinuities and Surface Conditions on Failure Under Repeated Stress," Engineering, 144:87-90 and 140-144, July 1937.

[4]H. F. Moore and J. B. Kommers, "An Investigation of the Fatigue of Metals", University of Illinois Engineering Experiment Station Bulletin, 124, 1921.

[5]W. N. Thomas, "Effect of Scratches and of Various Workshop Finishes Upon the Fatigue Strength of Steel", Reports and Memoranda No. 860, Aeronautical Research Committee, 2:542-568, March 1923.

[6]K. Matthaes, "Fatigue Strength of Airplane and Engine Materials", Technical Memorandum 743, N.A.C.A., p. 12, April 1934.

having file scratches decidedly reduced the fatigue strength of the material. Igarash and Fukai[7] mention in their report that a 9 to 24 percent increase in fatigue strength was obtained by very light polishing of duralumin specimens.

The data on early duralumin alloys with surface discontinuities are of significance in that they show that scratches are very detrimental to the life of structural components under repeated loading. These data, however, are of very little use to the present day designer of aircraft. Even the up to date fatigue data of the present day alloys cannot in most cases be used directly in design since the endurance limits are arrived at through the testing of polished specimens free from all "stress raisers" such as notches, holes, surface scratches, etc., whereas the materials used in fabrication are generally used in the "as received" condition. Aluminum sheet materials in the "as received" condition are far from being highly polished and very frequently have scratches of varying intensities. If the designer is concerned with fatigue in a particular design he must approximate the effect of the surface irregularities which may be present in the "as received" material. His approximations may be too conservative or may be unsafe, since up to this time no data on the effects of surface scratches on fatigue strength of aluminum alloys have been published. With this thought in mind the idea for this investigation was conceived.

Fatigue failures generally originate at a point on the surface

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[7] I. Igarash and S. Fukai, "On the Fatigue Test of Light Alloy Sheets", Transactions of the Society of Mechanical Engineers, Japan, 6:S-3, February 1940.

of a member, because usually, with normal stress distribution, the stress is greatest at the surface. Furthermore, stress concentrations are present at notches, fillets, scratches and similar irregularities, thus creating highly stressed focal points for the propagation of fatigue fractures. Although microscopical irregularities and other surface conditions usually have little influence on static strength, they often form the nucleus of fatigue failure. It has been attempted in this investigation to determine the intensity of concentration of stresses about scratches of various depths and to relate this information in such a form that it may be useful for design purposes. It is hoped that the presentation of such fatigue data will be of benefit to the designer in making more accurate calculations with regard to some surface irregularities in 24S-T and 24S-T Alclad.

MATERIAL

The two materials used in this investigation are the well known aircraft structural alloys, 24S-T, Army-Navy Specification AN-A-12, and 24S-T Alclad, Army-Navy Specification AN-A-13. Both materials were in the form of sheet and only one standard thickness, 0.040 inch, was used for the tests. The nominal chemical composition of the 24S-T is as follows: 4.4 percent copper, 1.5 percent magnesium, 0.6 percent manganese and the balance aluminum. The nominal chemical composition of the 24S-T Alclad is the same as that of the 24S-T for the core material, upon which a surface coating of pure aluminum is rolled, comprising approximately 10 percent of the total thickness of the sheet or 5 percent on each surface. Representative Stress-strain curves of the two sheets of material used are presented in Figures 1 and 2. The data reported are the averages of two tests for each material. The specimens used were the standard American Society of Testing Materials' Tension Test Specimen, described by Davis[8] in his handbook on materials testing. The tests were conducted on a Riehle Universal Hydraulic Testing Machine, a Huggenberger type extensometer being used for measuring the elongations. The mechanical properties of the materials thus derived are listed in Table I. These values were checked with those presented in the ANC-5[9] and were found to agree closely. The main purpose of these tests was for the determination of the yield point for the particular sheets of material and for defining the pertinent mechanical properties.

THE FATIGUE TESTING MACHINE

The tests to be reported here were run on a Sonntag Flexure Fatigue Machine, Model SF-2, with a capacity varying from 250,000 pounds per square inch on 0.025 inch sheet to 20,000 pounds per square inch on 0.250 inch sheet. The motive power is produced by a 1/4 horsepower synchronous motor operating at a constant speed of 1800 revolutions per minute. Three photographs, Figures 3, 4 and 5, show a sample loaded in the machine and indicate clearly the main features of loading.

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[8]H. E. Davis, G. E. Troxell and C. T. Wiskocil, The Testing and Inspection of Engineering Materials (New York: McGraw-Hill Book Company, Inc., 1941), p. 80, Fig. 48, Type B.

[9]Anonymous, "Strength of Aircraft Elements", ANC-5, Army-Navy-Civil Committee on Aircraft Design Criteria, Revised Edition, December 1942, Amendment-2, August 1946, p.5-6.

In the following discussion on the operation of the machine these photographs will be referred to in the mention of the various components.

The machine is a constant repeated force fatigue machine using an eccentric mass, A, to generate the force. By adjusting the eccentricity of the mass the force output may be read directly from the scale, B. The force is transmitted through rod, C, to load yoke, D. The travel of rod, C, is limited to the vertical, the side forces of the eccentric being absorbed by the pivot rod, E. The specimen is clamped in the load yoke by means of the pivot bar, F, clamp bar, G, and clamping bolts, H. The fixed end of the specimen is rigidly held in the pedestal, I, and clamped by bar, J, and bolts, K. Pedestal, I, is adjustable for different length specimens.

The machine is equipped with a micro-switch, L, which automatically shuts off the motor when the specimen breaks. Also, the machine is provided with counter, M, which registers the number of cycles to failure in a ratio of 1000 : 1.

As previously noted the force is applied by a rotating eccentric mass and remains a constant for any fixed value of eccentricity. A system of inertia compensation is used in order to maintain the force applied on the specimen constant irrespective of amplitude. This means of compensation absorbs all the inertia forces in the vibrating system so that the eccentric force alone acts on the specimen. A mathematical proof of the method is presented in the operating manual of the machine.[10] However, stated simply, this method is as follows: A spring, the tapered drive shaft, N, is used whose deflection constant is equal to the inertia forces of the vibrating system. As the deflection of the system increases the inertia forces in turn increase, but compensating this is the spring reaction which cancels the inertia forces. This leaves only the eccentric force or a repeated force of constant maximum value applied on the specimen. Since the system must be in resonance for the condition to hold, it is only valid for a given frequency and a given mass system. The synchronous motor, O, maintains constant frequency for the system and the variable poise weights, P, are provided in order to adjust for differences in the mass of the system when different weight specimens are used.

As was noted in the foregoing paragraph the mass of the system must be kept constant and for this reaxon it was necessary to calculate the poise setting for an 0.040 inch thick specimen in order that the machine be tuned to resonance. Using the calculated effective weight of the specimen,

$$W_e = .385 \times d \times t^{11}$$

where W_e = effective weight in pounds

d = density in pounds per cubic inch

and t = thickness of material in inches

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[10] Anonymous, "Instructions for Installation, Operation and Maintenance of Flexure Fatigue Testing Machine, Model SF-2, Serial No. 472875." Manual furnished by Sonntag Scientific Corporation, Greenwich, Connecticutt, prepared July 1947, Appendix Print No. 90273-S.

[11] *Ibid.*, p. 90450-S, sheet 3.

and referring this to graph No. 90452-S[12] the poise setting for an 0.040 inch thick specimen was determined. Graph No. 90452-S is a curve which was determined at the factory for the purpose of tuning this particular machine to resonance when using various thicknesses of material.

The last adjustment is that for the amount of force to be applied to give any desired stress. Graph No. 90446-S[13] is provided as a calibration curve of specimen stress per pound of force developed by the eccentric mass, against the thickness of the material. This curve is merely the adaptation of the familiar beam formula,

$$f = \frac{M\,y}{I}$$ [14]

where f = unit normal stress in psi.

M = bending moment on the cross-section in in.-lbs.

I = moment of inertia of section about its neutral axis in inches^4

y = distance parallel to the plane of bending between the point under consideration and the neutral axis, or one-half the thickness in inches for maximum stress, which occurs at the surface.

This formula may be modified to include the force of the eccentric mass

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[12]*Ibid.*, graph No. 90452-S.

[13]*Ibid.*, graph No. 90446-S.

[14]A. S. Niles and J. S. Newell, *Airplane Structures*, Second Edition, Vol. 1 (New York: John Wiley and Sons, Inc., 1938), p. 143.

and may be written

$$f = \frac{P\ l\ y}{I}$$

where $P \times l = M$

P = force of the eccentric mass in lbs.

l = the distance in inches from the load yoke to the point in question on the test section of the specimen.

The graph was found to be very useful in that it eliminated the making of individual calculations for each specimen each time the load was varied. Knowing the desired stress, it was only necessary to read the specimen stress per pound of force for a given thickness from the graph and divide this value into the desired stress for the machine setting on the eccentric.

Important considerations in running any specimen include: (1) adjusting and determining the values of the loads to be applied, and (2) determining the weakest section or point of minimum thickness.

THE FATIGUE SPECIMENS

A sketch of the specimen used for all of the fatigue tests reported here is shown in Figure 6, giving complete dimensions and mounting details. As may easily be deduced from the layout of the specimen, it incorporates as the test section a beam with constant bending stress. Since the bending stress is constant at any point on the test section between the two points where the radii become tangent to the straight sides, it is obvious that failure, as a result of fatigue stressing, may take place anywhere between the two extremities noted above. This fact may be validated by Figures 7 and 8, which show specimens of 24S-T and

24S-T Alclad, respectively, fractured at random locations along the test section.

Preparation: In preparing the specimens it was necessary at all times during the handling of the material to be extremely careful so that the specimens would not be marred or scratched. The specimens were first stack-drilled and then cut slightly oversize on a Do-All Metal Saw, using a template as a guide. Next, the specimens were stacked with dowel pins in the drill holes and were filed almost to size on a toolmaker's mechanical file. The finishing of the edges and final cutting down to size were done by hand, using No. 240 Aloxite Finishing Cloth and then polishing with crocus cloth. Finally the specimens were each polished with a liquid aluminum polish on the surfaces and edges. All specimens were carefully inspected for nicks or scratches on the surfaces and finished edges. The specimens of 24S-T were practically free from all surface scratches after the final polishing. However, the 24S-T Alclad specimens usually contained slight scratches or imperfections as a result of the handling, due to the softer surface of the pure aluminum coating.

It was necessary to check with a micrometer the thickness of each specimen, since there was a considerable variation in thickness of the finished specimens in spite of the fact that they were all cut from the same sheet. The 24S-T specimens varied from a thickness of 0.0382 inch to a thickness of 0.0392 inch and likewise the 24S-T Alclad specimens varied from a thickness of 0.040 inch to a thickness of 0.0412 inch.

Grain Direction: All specimens were cut with the centerline parallel to the direction of rolling of the sheet in order to give higher values of cycles and also to provide uniformity of tests. Brick and Phillips[15] have investigated the effect of grain direction on 24S-T and 24S-T Alclad and arrived at the following conclusions: (1) At 5×10^7 cycles for 24S-T samples cut parallel to the direction of rolling, a value of 20,500 $\pm$ 1000 psi was indicated and for samples cut perpendicular to the direction of rolling, a value of 18,500 $\pm$ 2000 psi was indicated. (2) For 24S-T Alclad at 5×10^7 cycles for specimens cut parallel, 13,000 $\pm$ 1000 psi was indicated and for specimens cut perpendicular, 11,500 $\pm$ 1000 psi was indicated. As can be noted from these results it was necessary to select a given grain direction with respect to the specimen in order to maintain uniformity and also since the investigation was rather extensive in its entirety it was necessary to limit the study to only one grain direction.

Scratches: Five different roughnesses of commercial abrasives were used to scratch the specimens, namely, crocus cloth, Numbers 240, 180 and 100 Aloxite Finishing Cloth and Number 60 Jewel Garnet Sandpaper. Both sides were uniformly roughened over the entire test section, on both sides, with a given abrasive, applying the force by hand. All scratches were made transverse to the direction of stress in order to obtain the greatest reductions in fatigue strength. Figures 9 and 10 show unbroken polished and scratched samples of both materials used.

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[15] R. M. Brick and A. Phillips, "Fatigue and Damping Studies of Aircraft Sheet Materials: Duralumin, Alloy 24S-T, Alclad 24S-T and Several 18:8 Type Stainless Steels", Transactions, American Society for Metals, 29:441, June 1941.

Horger[16] states that surface finish marks in planes transverse to the direction of stress have detrimental effects on fatigue strength. He also cites the service performance of springs and axles where longitudinal cracks were found to have little or no influence on the bending fatigue strength. Transverse scratches have a considerably more detrimental effect on fatigue life than do longitudinal scratches because, in bending, the normal stresses are perpendicular to the transverse scratches. As a scratch, nick or any other type of discontinuity provides nuclei for stress concentrations, the entire width described by the transverse scratches tends to upset or retard the flow or normal stresses and hence stress concentrations are present all along the transverse scratches. In the case of longitudiani scratches the effect is relatively small, since the scratches are in line with the normal stresses and hence do not tend to retard the flow to such a degree as do the transverse scratches.

Since the entire test section of each specimen was thoroughly roughened, a great number of scratches were imparted in a small area, thus making the scratches lie side by side or overlap. For this reason it is not proposed that the stress concentration factors, obtained from the tests reported, are the highest for a given depth of scratch, but merely average stress concentration factors, presented for the condition where scratches are very close together. Roark[17] explains that a single isolated "stress raiser" has a worse effect

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[16] Horger, _op. cit._, p. 492.

[17] R. J. Roark, _Formulas for Stress and Strain_, Second Edition (New York: McGraw-Hill Book Company, Inc., 1943), p. 32.

than do a number of similar "stress raisers" grouped close together. In other words, one "stress raiser" closely adjacent to another "stress raiser" would tend to relieve, to a certain degree, the stresses on the other "stress raiser" and vice versa. Thus it is reasonable to say that tests run with specimens having only a single transverse scratch will provide stress concentration factors of somewhat greater magnitude than those presented in this paper.

Depths of Scratches: Measurement of the depth of scratch resulting from the various abrasives was done by means of a Baush and Lomb Research Metallograph. A magnigication of 2175 times was found to give a clear and distinct view of the grooves and ridges. By first focusing on a ridge and then focusing on the adjacent groove it was possible to determine the depth of scratch through the differential of focal length. The microscope was provided with a calibrated adjusting knob, thus simplifying the calculation of the depth of scratch to merely taking the difference in readings for the ridge and groove. As the scratches imparted to the surface were not uniform in depth, ten readings were taken on a given scratched specimen and the average was taken as being representative of the scratches on the entire surface of the specimen. Generally, each single reading of depth varied from about 5 to 15 percent of the average. In a few cases, with the coarser abrasives, the difference was as much as 25 percent. This variation may be attributed to the method of applying the scratches. The average scratch depths for the various abrasives are presented in Table II. The contention that the average value of depth is valid may also be justified as being reasonable by the fact that the values reported provide a smooth curve when plotted against the grit number of the abrasive. This graph is shown in Figure 11.

TEST PROCEDURE

The specimen is placed in the machine in a horizontal position as shown in Figures 5 and 6. One end of the specimen is fixed rigidly and the other end clamped in the load yoke. The desired load is adjusted by means of the eccentric mass, and once the machine is started it will continue until failure occurs and the limit switch automatically stops the motor.

The tests for each particular curve were begun with the high stresses, gradually decreasing the stress in increments of about 2 to 3 thousand psi for each succeeding specimen. In this way the general trend of the curves was obtained, and it enabled the operator to predict approximately the life of a specimen at a given lower stress.

The high stresses for all tests were determined as those necessary to give only a few thousand reversals of stress. In all cases these stresses never exceeded the yield point of the material. Specimens stressed in the lower range were generally loaded so that the life would not exceed 10 million cycles. Almost all the tests were continued to failure, however, some few specimens were removed even though failure had not occured after 10 to 15 million cycles of stress. Such points are indicated on the plots with the conventional horizontal arrow at the point where the test was discontinued.

The curves of the polished specimens were run first, in order to determine the "par value" and also as a check to insure correct operation of the machine. These curves agree closely with similar curves as reported by Brick and Phillips[18] for polished 24S-T and 24S-T Alclad, with the difference that the values reported in this investigation are slightly higher in all cases. Since 1941, when Brick and Phillips carried out their investigation, there have been notable improvements in the processing of aluminum sheet, thus bettering the mechanical properties of the sheet. Hence it is reasonable to assume that similar improvements have resulted with respect to fatigue strength.

Next, the curves of the scratched specimens were run in successive order with respect to the scratch depth, the specimens with the lightest scratches being run first.

DISCUSSION OF RESULTS

The results of all fatigue tests were plotted in the form of S-N diagrams, stress versus number of cycles. Semi-logarithmic paper was used for plotting the results in keeping with conventional methods of presenting fatigue results.

Fatigue Results of 24S-T: Figures 12, 13, 14, 15 and 16 show the results of fatigue tests on 24S-T specimens with transverse scratches made by the various abrasives. The experimental points obtained are clearly indicated on the graphs and the curves are faired through them. In addition, the fatigue curve of polished specimens is included on each graph for purpose of comparison. Figure 17, which is merely a compilation of all the fatigue curves for the 24S-T specimens resulting from the investigation, is also presented in order to show the relative effects of the various abrasives on the fatigue strength.

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[18] Brick and Phillips, op. cit., p. 440.

There is a considerable degree of scatter in the experimental points in all the curves, however, in comparison it should be noted that other experimental fatigue tests show a similar scatter. In fact, some investigators are of the opinion that fatigue results should be plotted as a scatter band and not as a single curve. There are several possible reasons for the scatter of points, some being as follows: (1) slight errors in setting required loading, (2) non-uniformity of scratches, (3) slight errors in machining and finishing, (4) possible error in reading calibration curve of machine, (5) the effect of work hardening, (6) metallurgical differences in the samples, and (7) the actual nature of the fatigue phenomenon.

Figure 17, the graph showing the relative effects of the various abrasives, indicates clearly that there is a distinct progressive reduction in fatigue life for any predetermined stress with the increase in scratch depth. Also, the greater the roughness imposed, the greater the reduction in fatigue strength. The specimens scratched with crocus cloth showed the least reduction, since the scratches produced were very slight, and as might be supposed, the greatest reductions were obtained from specimens scratched with the No. 60 sandpaper, the coarsest abrasive used.

In all the tests run there was no indication of an endurance limit for either of the materials. By referring to Figure 17 it is seen that there is no leveling-off of the curves as in the case of steel. Instead there is a definite downward slope. Many other investigators have cited this fact with respect to aluminum and its alloys.

Fatigue Results of 24S-T Alclad: Figures 18, 19, 20, 21 and 22 show the results of fatigue tests on 24S-T Alclad specimens with transverse scratches made by the various abrasives. Here likewise, the experimental points are indicated on the graphs and the curves are faired through them. Again the curve of the polished specimens is included with each graph in order to illustrate the reduction in fatigue strength due to the surface roughness. Figure 23, similar to Figure 17 for the 24S-T, shows the curves of all the 24S-T Alclad specimens and the relative effects of the various abrasives on the fatigue strength.

The degree of scatter of points for the 24S-T Alclad specimens is less than that of the 24S-T specimens. This is probably an indication that surface scratches are not so detrimental to the fatigue strength of alclad material as to the unclad material. However, the other considerations for the scatter of points in the unclad material also apply to the alclad material.

Referring to Figure 23, the graph showing the relative effects of the various abrasives, it is seen that there is a distinct progressive reduction in fatigue life with successive cycles of stress, but not so great as in the case of the unclad material. Likewise the more rougher abrasive produced greater reductions in fatigue strength but in much smaller increments than those on the 24S-T, even though the average depths of scratches were greater. The specimens scratched with crocus cloth showed the least reduction and, as might be expected, the specimens scratched with the No. 60 sandpaper showed the greatest reductions.

The fact that greater reductions in fatigue strength were obtained for 24S-T than for 24S-T Alcaid does not imply that the alclad material is the better. 24S-T is superior to 24S-T Alclad where static strength is concerned and the same happens to be true in the case of fatigue strength in spite of the greater reduction in strength of the former. As an example, compare the effect of a given scratch depth on the fatigue properties of both materials. Referring to Table II it is seen that No. 60 sandpaper produces approximately the same depth scratch on 24S-T as does No. 100 Aloxite on 24S-T Alclad. Now referring to Table III it is seen that for No. 60 sandpaper on 24S-T at 10^7 cycles, a strength of 16,000 psi is reported. In contrast to this, it is seen that a value of 13,300 psi is reported for No. 100 Aloxite on 24S-T Alclad at 10^7 cycles in Table IV. The stress concentration factors for 24S-T are higher, but the actual fatigue strength is also higher, because of the initially higher fatigue strength of the 24S-T. In analyzing fatigue strengths of the two materials, one must also bear in mind that the alclad material is more susceptible to scratches than is the unclad material.

During the testing of the polished alclad specimens it was noted that after a certain time, depending upon the stress, a large number of cracks in the weak aluminum coating began to appear. These cracks propagated into the alloy core and hence produced failure. No doubt, since such cracks are inherent to fatigued alclad, the addition of scratches with the abrasives merely hastened a process which was to occur anyway. For this reason the effect of the various abrasives was not as great on the alclad material as on the unclad. In all cases the depth of scratch never penetrated through the aluminum coating of the material, the greatest average depth of scratch being 0.0001981 inch (see Table II), and the thickness of the aluminum coating being approximately 0.002 inch.

Stress Concentration: When there is an abrupt change in cross section a considerable disturbance in stress distribution results and the maximum stresses encountered at the discontinuity are usually much greater than would be indicated by the change in cross section. Any type of discontinuity such as a scratch, notch, hole, etc., may cause the stresses in a member to be magnified locally, thus producing what is known as stress concentration. If f is the calculated stress in the section without a discontinuity, as determined by conventional methods, and f_{max} the stress at the point affected by the discontinuity, then this maximum stress may be represented as a function of the calculated stress, or

$$f_{max} = K f$$ [19]

where K is the stress concentration factor, and is dependent upon the character and relative size of the discontinuity.

Many investigators, concerned with stress concentration, have devised both theoretical and special experimental methods for determining stress concentration factors for numerous configurations of discontinuities. However, no such method is feasible in the case of scratches since there is no uniformity in their configuration.

Since, in all cases investigated, the scratched specimens failed at lower numbers of cycles than did the polished specimens at the same

[19] S. Timoshenko, Strength of Materials, Part II, Advanced Theory and Problems, Second Edition (New York: D. Van Nostrand Company, Inc., 1941), p. 337.

stress, it is obvious that there is a definite concentration of stresses at the scratches. Assuming that the scratched specimens are operating at a stress greater than that obtained from the simple beam formula for a given load, it is evident that there exists a factor of concentration such that,

$$f_{max} = K_f \times f$$

where f_{max} is the stress at which the scratched specimens are operating, f is the stress as obtained by the simple beam formula, for a given load, and K_f is the stress concentration factor for repeated flexure fatigue. Hence it may now be said that for a given number of cycles a scratched specimen was operating at the same stress as was a given polished specimen, and that the stress concentration factor, K_f, must be applied to the simple beam formula in order to obtain the actual operating stress.

Under the foregoing assumptions it was possible to calculate the stress concentration factors for the scratches imposed by the various abrasives. Table III gives the repeated flexure fatigue strengths of 0.040 inch 24S-T with transverse surface scratches due to the several abrasives and the corresponding stress concentration factors. Table IV gives similar data for 24S-T Alclad. These stress concentration factors were calculated by dividing the stress of a scratched specimen, at a given number of cycles, into the stress of the polished specimen, at the same number of cycles. These factors are calculated for six different locations on the curve, thus obtaining six factors which in most cases are fairly constant for a given abrasive. The factors obtained for low numbers of cycles are generally higher than those obtained for high numbers of cycles. However, the six values were averaged and presented as an average stress concentration factor. By doing this the average stress concentration factors will be more conservative in the lower stress range. Figure 24 shows a plot of these average stress concentration factors against the average depth of scratch as produced by the several abrasives. From these curves one may conclude that a given scratch depth has less effect on the fatigue life of 24S-T Alclad than a similar scratch depth has on 24S-T. However, if the scratch were of such magnitude as to penetrate the pure aluminum coating of the alclad material, it is likely that the effect would be more in order with that of the unclad material.

Size Effect: The effect of size is a very important consideration when applying fatigue data obtained from small specimens to the design of large components. It has been noted by numerous investigators[20] in size effect studies of metal bars and shafts, both notched and unnotched, that fatigue strengths obtained as a result of testing small specimens are greater than fatigue strengths obtained through the testing of large specimens, and that notch sensitivity increases as the actual size increases. The actual fatigue data of light alloy sheet with respect to size effect is, indeed, meager. Buchmann[21] investigated several light alloys, Mg-Al6("Elektron AZM"), GMg-Al("Elektron A9V") and Al-Cu-Mg("Igedur 26") with respect to size effect with the follow-

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[20] Battelle Memorial Institute: Prevention of the Failure of Metals Under Repeated Stress, (New York: John Wiley and Sons, Inc., 1941), p. 123.

[21] W. Buchmann, "Influence of Cross-Sectional Area on Fatigue Strength", Engineer's Digest, 3:137, March 1945.

ing results:

(a) There was a pronounced drop in the flexural fatigue strength with increasing size, especially in the range of small cross-sectional areas, (5 to 15 mm. dia.).

(b) Beyond a certain limit, (30 mm. dia.), the rate of drop in flexural fatigue strength is only slight; the curves tended asymptotically toward the fatigue strength due to reversed axial loads. The excess strength on reversed flexure over the asymptotic value is explained by the stabilizing effect of the slightly stressed inner fibers on the highly stressed outer fibers. This effect obviously depends on the stress gradient.

(c) The fatigue strength of unnotched samples due to reversed axial loads is independent of scale factor, With a notched sample, however, there is a stress gradient and consequently, due to the stabilizing effect there is an influence of size on the fatigue strength.

(d) With fatigue due to alternating torsion there is a distinct influence of the size of the test samples, even when unnotdhed.

It is obvious from the findings of Buchmann that the results of this investigation are limited to the design of small components and to sheet of the same gage tested unless adequate size effect correction factors are applied.

Application of Data of Design: Fatigue data as obtained from the laboratory through the testing of polished specimens are not directly applicable to design, but must be modified to meet the particular design conditions. The data herein presented is one step in the direction of reducing the designer's problem of modifying fatigue data when the design condition involves surface irregularities of the same nature as investigated in this paper. When applying the data to large components adequate size effect factors should be used to correct the data. Also, since the stress ranges encountered in design are not usually of the order of completely reversed stress, the data should be adjusted to meet the particular range of stress in question. Methods such as the endurance diagram, as explained by Maleev[22], may be set up to find endurance strengths for various stress ratios.

Assuming that the size effect is of the same order as for the results of this investigation and that the range of stress is that of complete reversals of stress, then the problem of predicting the life of a 24S-T or 24S-T Alclad component becomes very simple. Knowing the operating stress of the component and the surface condition, reference to Figure 24 will give the stress concentration factor for the particular surface condition. The operating stress is multiplied by the factor in order to obtain the true operating stress of the component. This true operating stress is now referred to an S-N curve for polished specimens and the corresponding number of cycles is the life of the scratched component.

The stress concentration factors reported are believed to be reliable for application to design. They should be applied to design stresses in computing the margins of safety.

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[22] V. L. Maleev, Machine Design, Second Edition, (Scranton, Pennsylvania: International Textbook Company, 1946), p. 47.

CONCLUSIONS

From the foregoing presentation of the results of this investigation the following conclusions are drawn:

1. Surface scratches definitely reduce the flexure fatigue strength of 24S-T and 24S-T Alclad sheet material. The greater the depth of surface scratch the greater the reduction.

2. Surface scratches are more detrimental to the fatigue properties of 24S-T than to 24S-T Alclad, provided the scratches are not through the pure aluminum coating. Even though the reduction in fatigue strength for a given scratch depth is greater for 24S-T than for 24S-T Alclad, 24S-T still exhibits higher values of fatigue strength in pounds per square inch.

3. Average stress concentration factors have been determined for small surface scratches in 0.040 inch 24S-T and 24S-T Alclad materials. These concentration factors may be applied to design provided the design conditions are similar to those of the investigation.

4. The stress concentration factors should be applied to design loads in computing margins of safety.

5. Further study should be made with heavier gage material having surface scratches in order to investigate the size effect phenomenon.

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APPENDIX I, Tables

TABLE I

MECHANICAL PROPERTIES OF 24S-T AND 24S-T ALCLAD SHEETS USED IN FATIGUE TESTS

MATERIAL	E, MODULUS OF ELASTICITY, P.S.I	YIELD STRENGTH, P.S.I.	ULTIMATE TENSILE STRENGTH, P.S.I.
24 S-T	10.2×10^6	51,500	68,000
24S-T ALCLAD	10^7	49,500	63,000

TABLE II

AVERAGE DEPTH OF SCRATCH FOR VARIOUS ABRASIVES ON 24S-T AND 24S-T ALCLAD

MATERIAL	ABRASIVE	AVERAGE DEPTH OF SCRATCH, INCH
24 S-T	CROCUS CLOTH	.0000508
	NO. 240 ALOXITE	.0000721
	NO. 180 ALOXITE	.0000811
	NO. 100 ALOXITE	.0001070
24 S-T	NO. 60 SANDPAPER	.0001573
24 S-T ALCLAD	CROCUS CLOTH	.0000551
	NO. 240 ALOXITE	.0000866
	NO. 180 ALOXITE	.0001102
	NO. 100 ALOXITE	.0001495
24S-T ALCLAD	NO. 60 SANDPAPER	.0001981

TABLE III

REPEATED FLEXURE FATIGUE STRENGTHS OF 0.040 INCH 24 S-T SHEET WITH TRANSVERSE SURFACE SCRATCHES DUE TO SEVERAL ABRASIVES AND THE CORRESPONDING STRESS CONCENTRATION FACTORS. STRESSES IN P.S.I.

		CONDITION OF SURFACE										
		POLISHED	CROCUS CLOTH		NO. 240 ALOXITE		NO. 180 ALOXITE		NO. 100 ALOXITE		NO. 60 SANDPAPER	
		STRESS	STRESS	FACTOR	STRESS	FACTOR	STRESS	FACTOR	STRESS	FACTOR	STRESS	FACTOR
CYCLES	5×10^4	42,500	38,000	1.118	35,500	1.196	35,000	1.213	34,600	1.228	29,700	1.431
	10^5	36,000	32,800	1.097	32,100	1.121	31,100	1.157	30,350	1.186	26,800	1.343
	5×10^5	30,100	27,500	1.094	26,600	1.131	25,900	1.162	25,100	1.198	21,700	1.387
	10^6	28,500	26,000	1.096	25,200	1.131	24,400	1.168	23,700	1.202	20,400	1.396
	5×10^6	25,350	22,900	1.106	22,400	1.131	21,650	1.170	20,950	1.209	17,200	1.472
	10^7	24,150	21,750	1.110	21,350	1.131	20,600	1.172	20,000	1.207	16,000	1.510
AVERAGE STRESS CONCENTRATION FACTOR				1.103		1.140		1.173		1.203		1.422

TABLE IV

REPEATED FLEXURE FATIGUE STRENGTHS OF 0.040 INCH 24S-T ALCLAD SHEET WITH TRANSVERSE SURFACE SCRATCHES DUE TO SEVERAL ABRASIVES AND THE CORRESPONDING STRESS CONCENTRATION FACTORS. STRESSES IN P.S.I.

	CONDITION OF SURFACE										
	POLISHED	CROCUS CLOTH		NO. 240 ALOXITE		NO. 180 ALOXITE		NO. 100 ALOXITE		NO. 60 SANDPAPER	
CYCLES	STRESS	STRESS	FACTOR	STRESS	FACTOR	STRESS	FACTOR	STRESS	FACTOR	STRESS	FACTOR
5×10^4	35,800	32,500	1.101	30,400	1.178	28,500	1.256	27,900	1.282	27,150	1.318
10^5	28,900	26,200	1.102	24,400	1.183	23,250	1.242	22,600	1.278	22,100	1.307
5×10^5	19,200	17,800	1.078	17,100	1.122	16,750	1.146	16,250	1.181	15,600	1.231
10^6	17,650	16,600	1.063	15,800	1.117	15,600	1.131	15,100	1.169	14,350	1.230
5×10^6	15,900	14,900	1.067	14,250	1.116	14,000	1.136	13,750	1.156	12,850	1.237
10^7	15,300	14,350	1.066	13,750	1.112	13,550	1.129	13,300	1.150	12,400	1.233
AVERAGE STRESS CONCENTRATION FACTOR			1.079		1.139		1.172		1.202		1.259

APPENDIX II, Figures

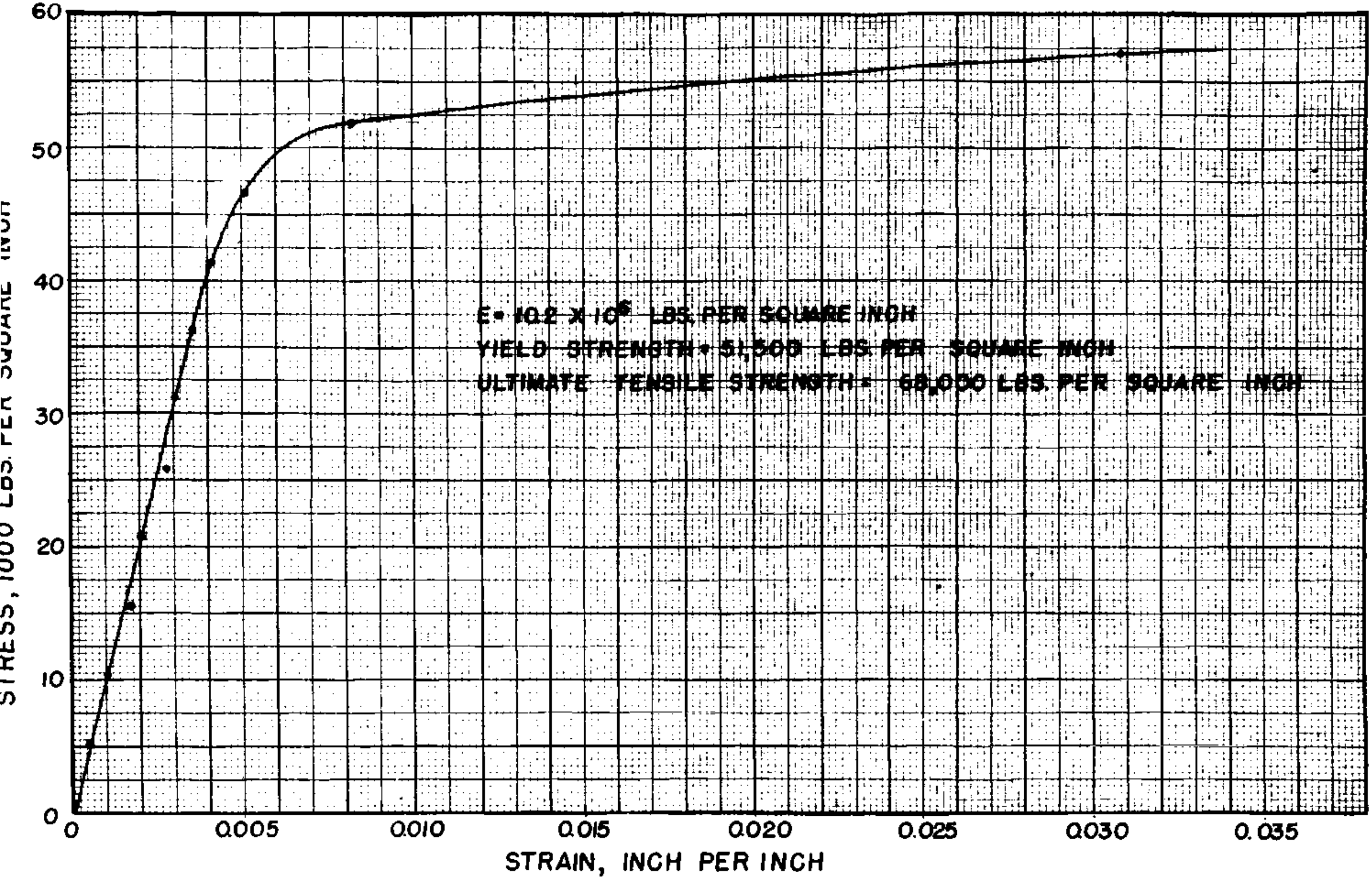


FIGURE 1. STRESS-STRAIN CURVE OF 0.040 INCH
24S-T SHEET MATERIAL USED IN FLEXURE FATIGUE TESTS

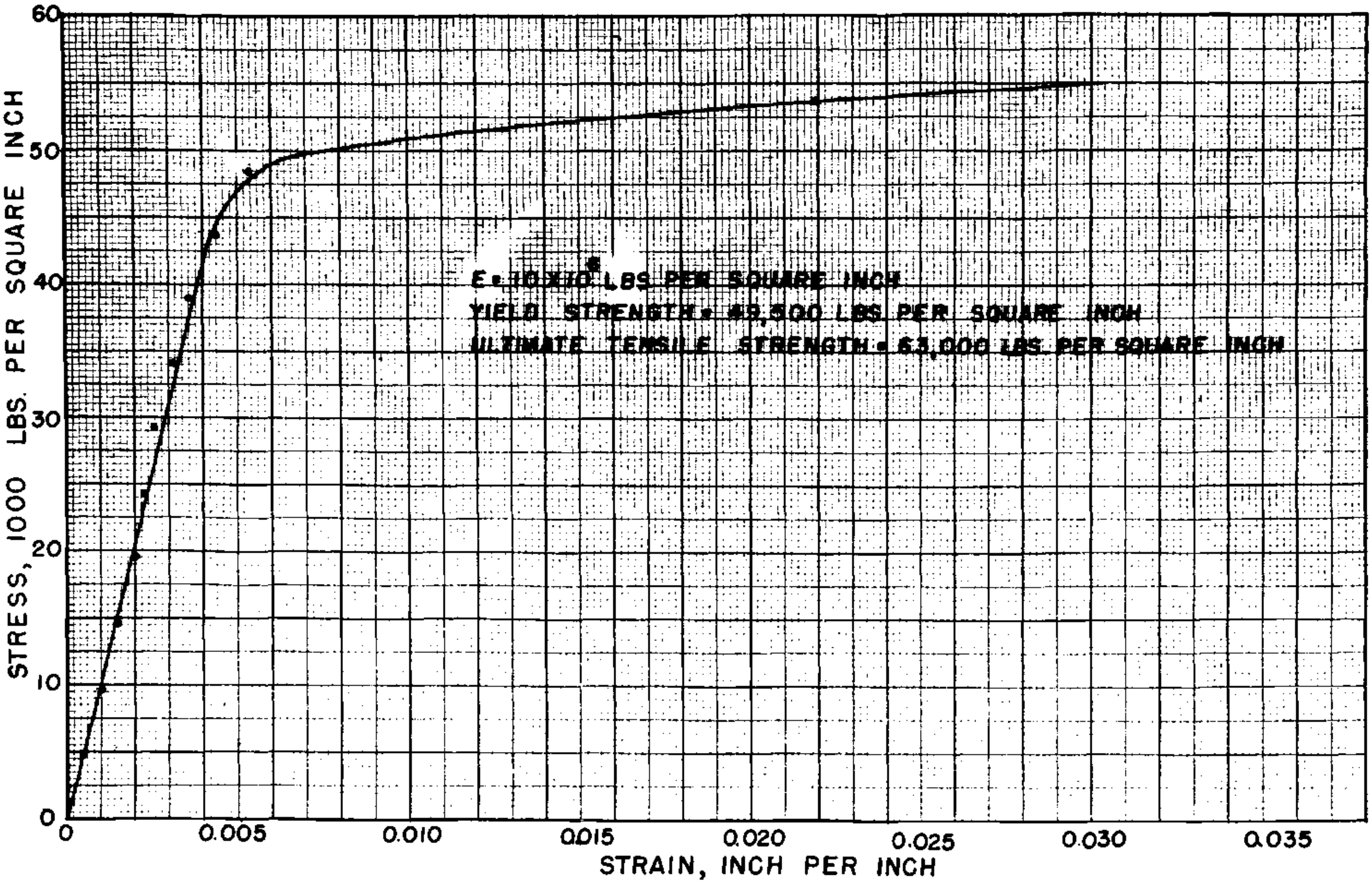


FIGURE 2. STRESS-STRAIN CURVE OF 0.040 INCH 24 S-T ALCLAD SHEET MATERIAL USED IN FLEXURE FATIGUE TESTS

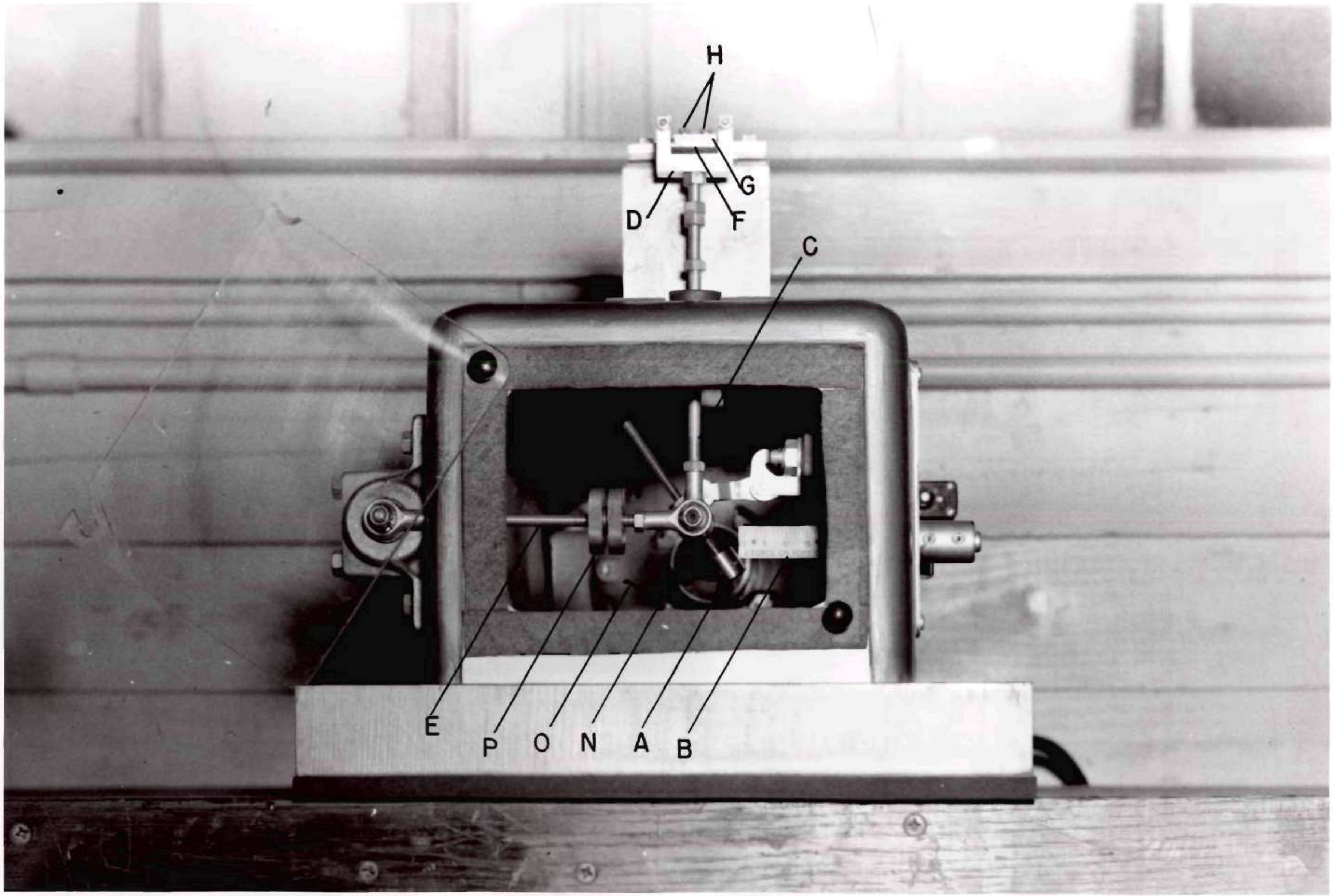


FIGURE 3. SONNTAG FLEXURE FATIGUE MACHINE, MODEL SF-2

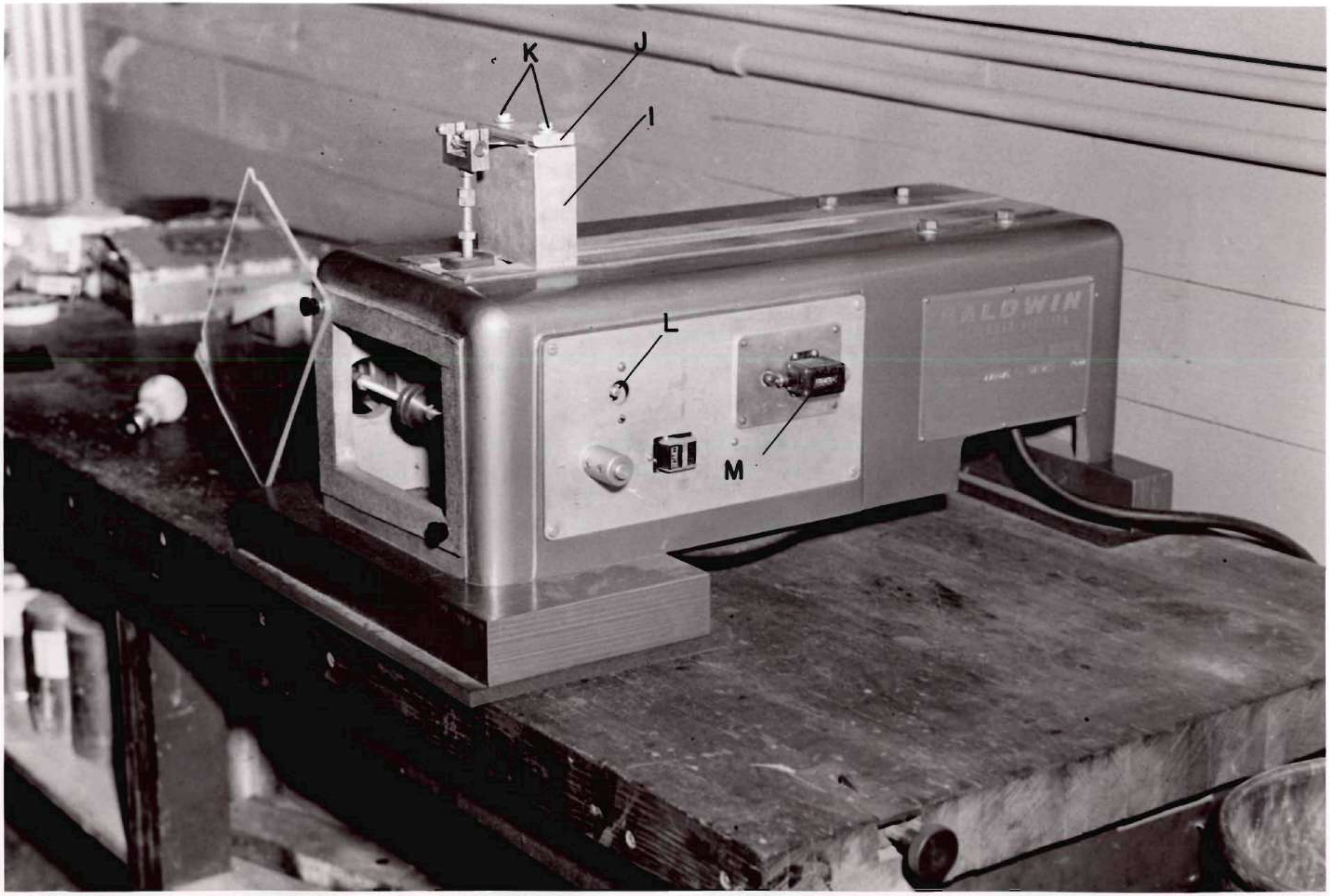


FIGURE 4. SONNTAG FLEXURE FATIGUE MACHINE, MODEL SF-2

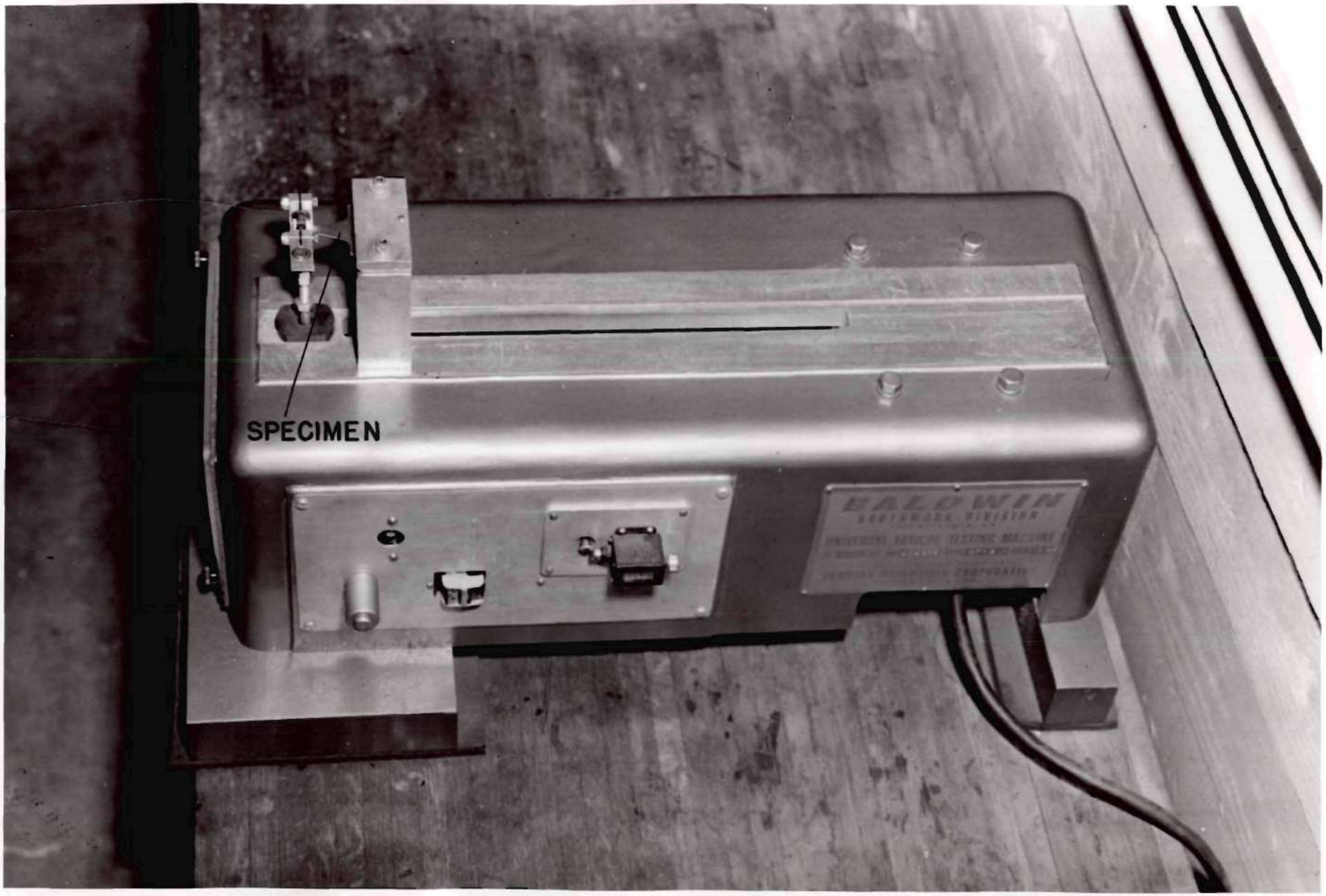
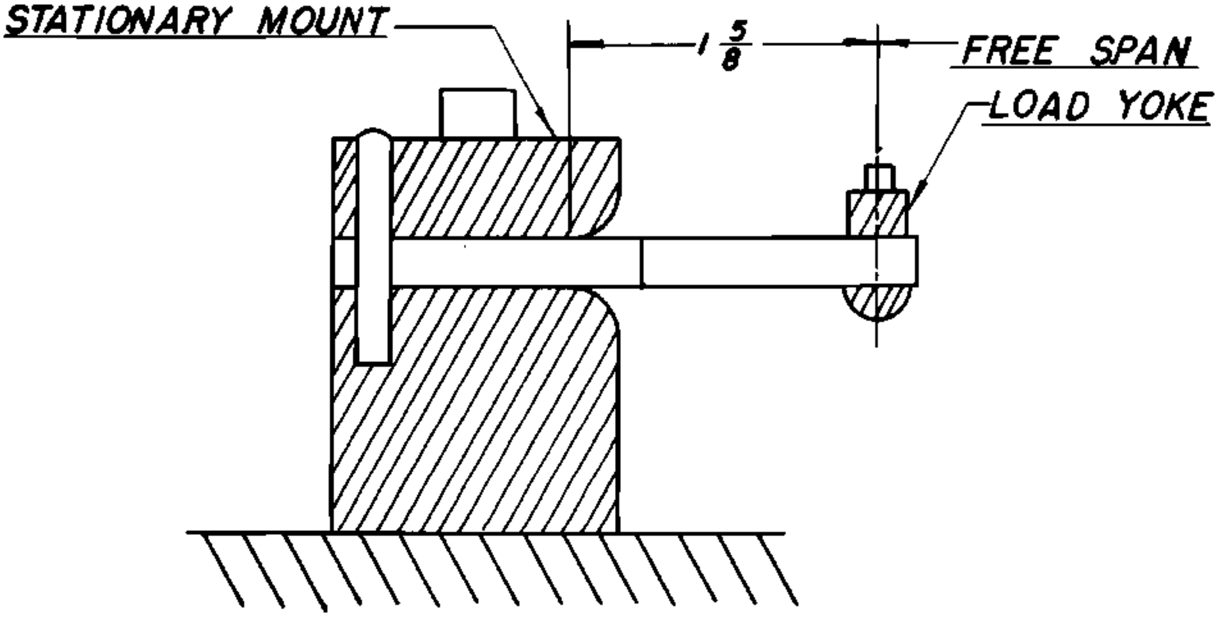
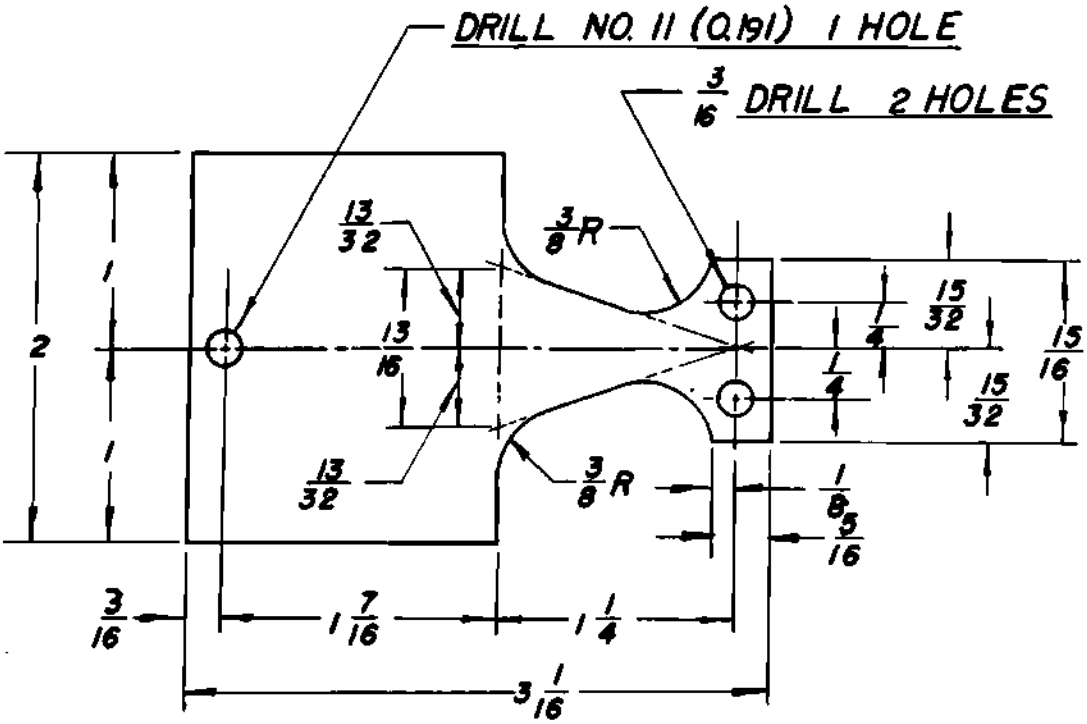


FIGURE 5. VIEW SHOWING SPECIMEN LOADED IN FATIGUE MACHINE

FIGURE 6.
SPECIMEN AND MOUNTING DETAILS



CROSS SECTIONAL VIEW OF SPECIMEN MOUNTING



SPECIMEN DETAILS

ALL DIMENSIONS IN INCHES

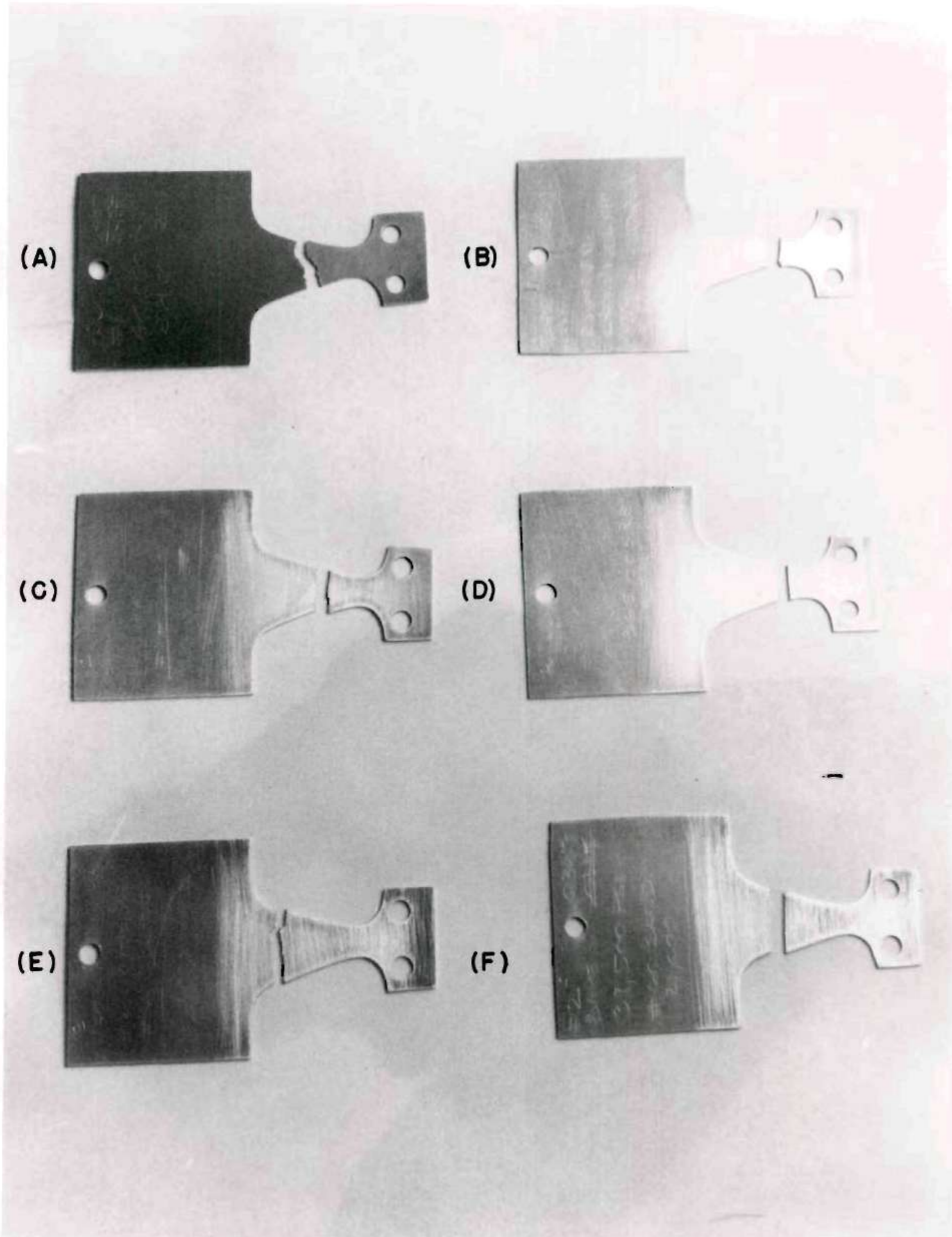


FIGURE 7. FRACTURED 24 S-T SPECIMENS

TYPE SURFACE FINISH

(A) POLISHED, (B) CROCUS CLOTH, (C) NO. 240 ALOXITE

(D) NO. 180 ALOXITE, (E) NO. 100 ALOXITE, (F) NO. 60 SANDPAPER

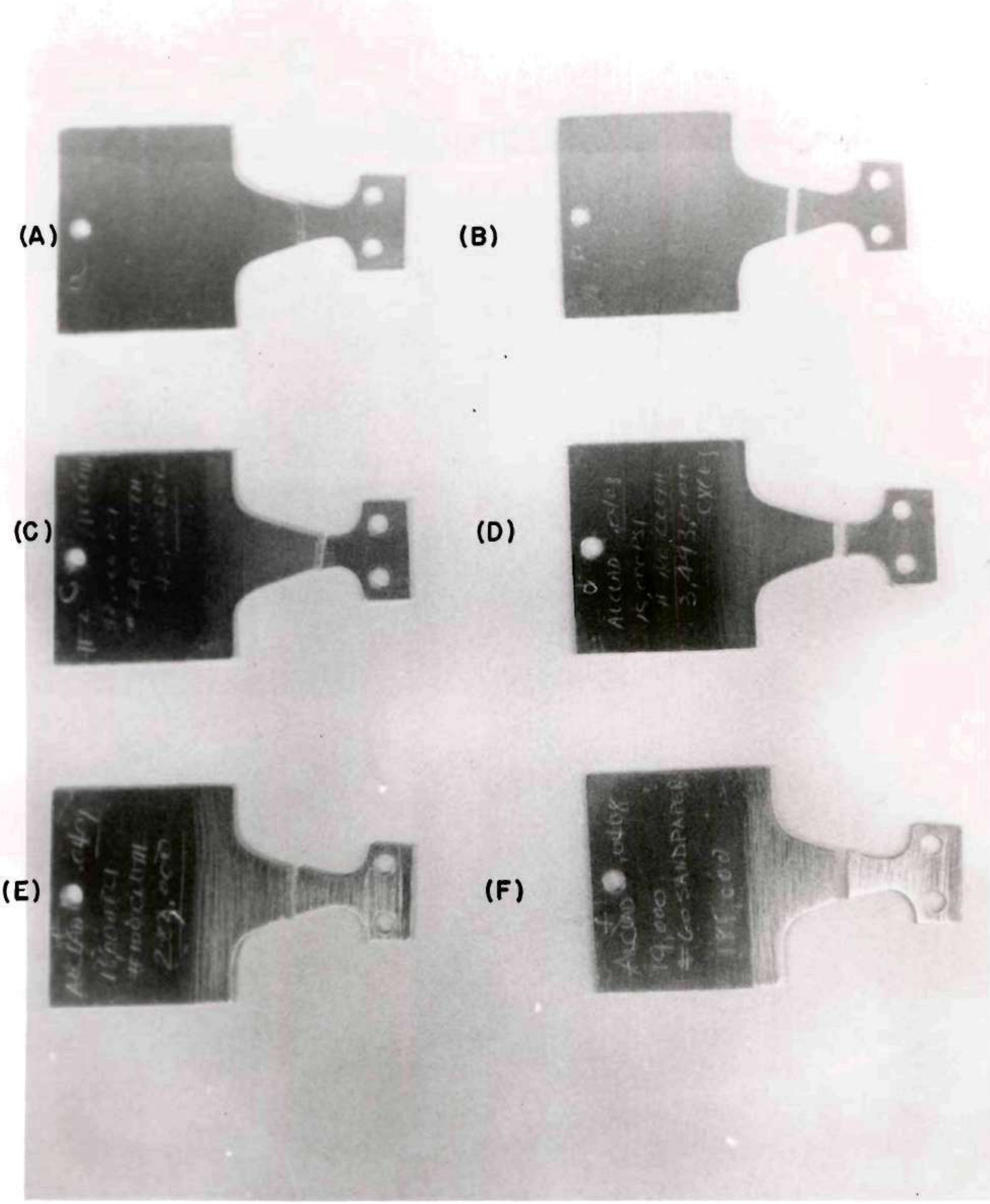


FIGURE 8. FRACTURED 24S-T ALCLAD SPECIMENS
TYPE SURFACE FINISH
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(D) NO. 180 ALOXITE, (E) NO. 100 ALOXITE, (F) NO. SANDPAPER

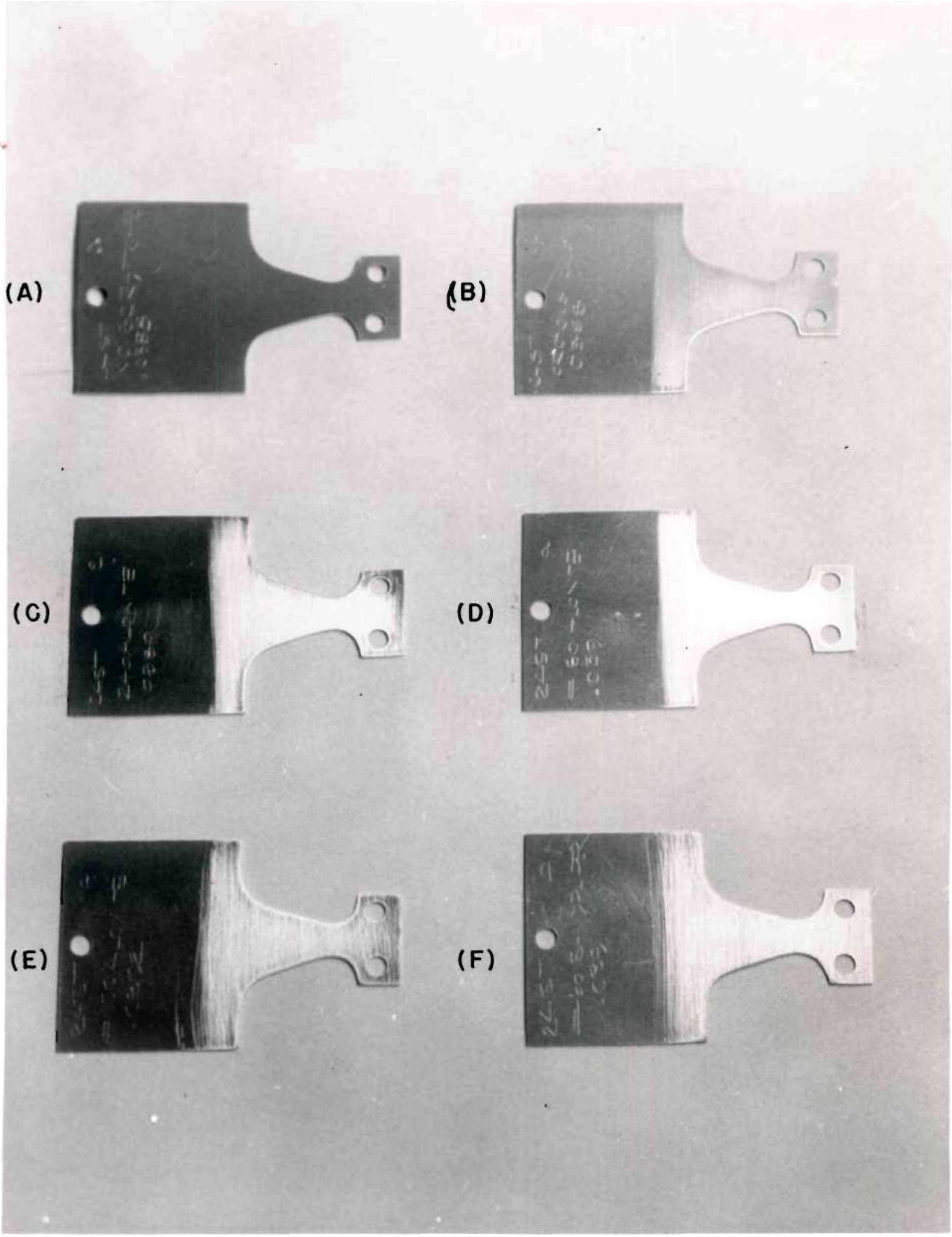

FIGURE 9. 24S-T SPECIMENS BEFORE FRACTURE
TYPE SURFACE FINISH

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(D) NO. 180 ALOXITE, (E) NO. 100 ALOXITE, (F) NO. 60 SANDPAPER

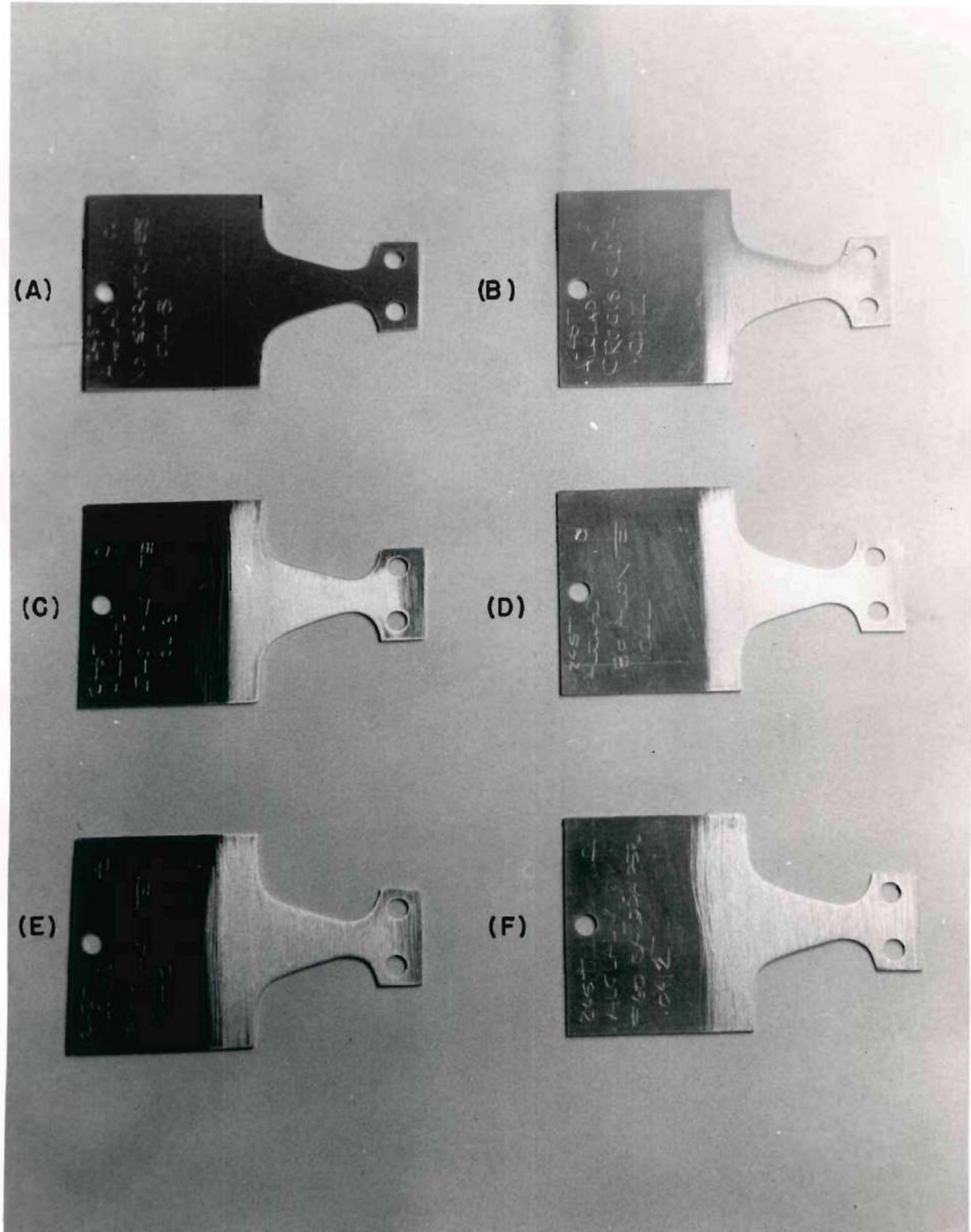

FIGURE 10. 24S-T ALCLAD SPECIMENS BEFORE FRACTURE

TYPE SURFACE FINISH

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(D) NO. 180 ALOXITE, (E) NO. 100 ALOXITE, (F) NO. 60 SANDPAPER

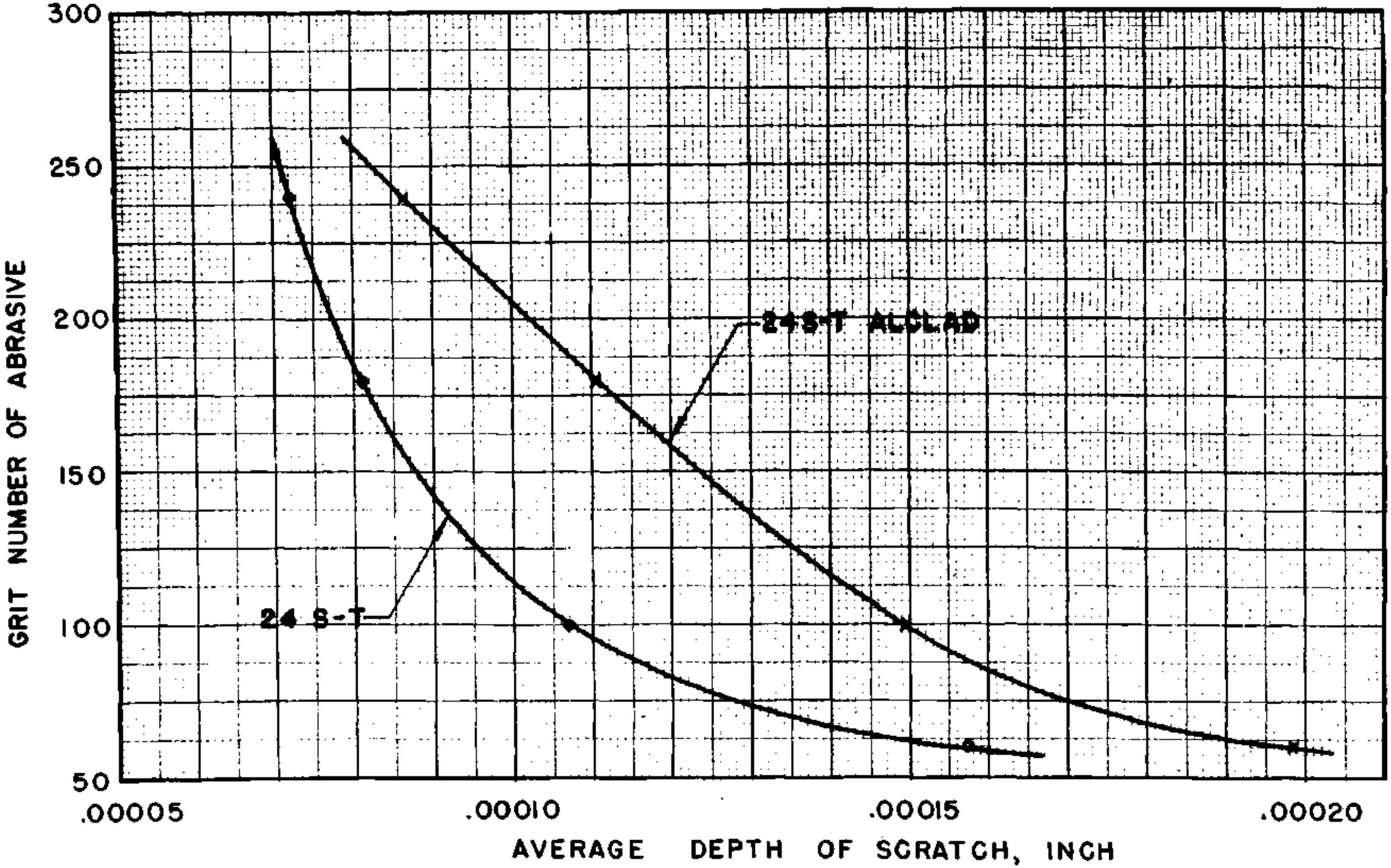

FIGURE 11. VARIATION OF AVERAGE DEPTH OF SCRATCH WITH GRIT NUMBER OF ABRASIVE IN 24S-T AND 24S-T ALCLAD

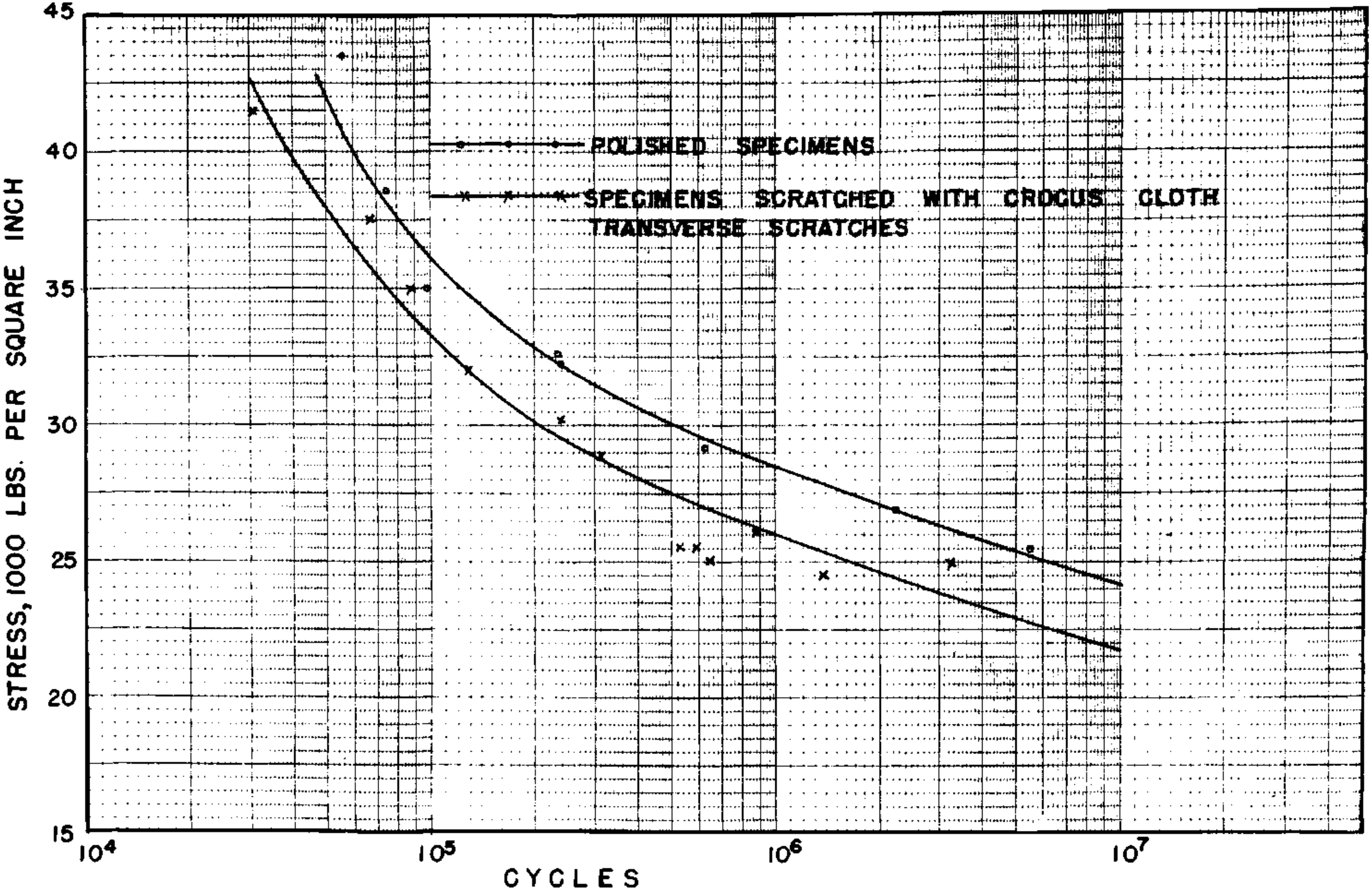

FIGURE 12. REPEATED FLEXURE FATIGUE
0.040 INCH 24 S-T SHEET

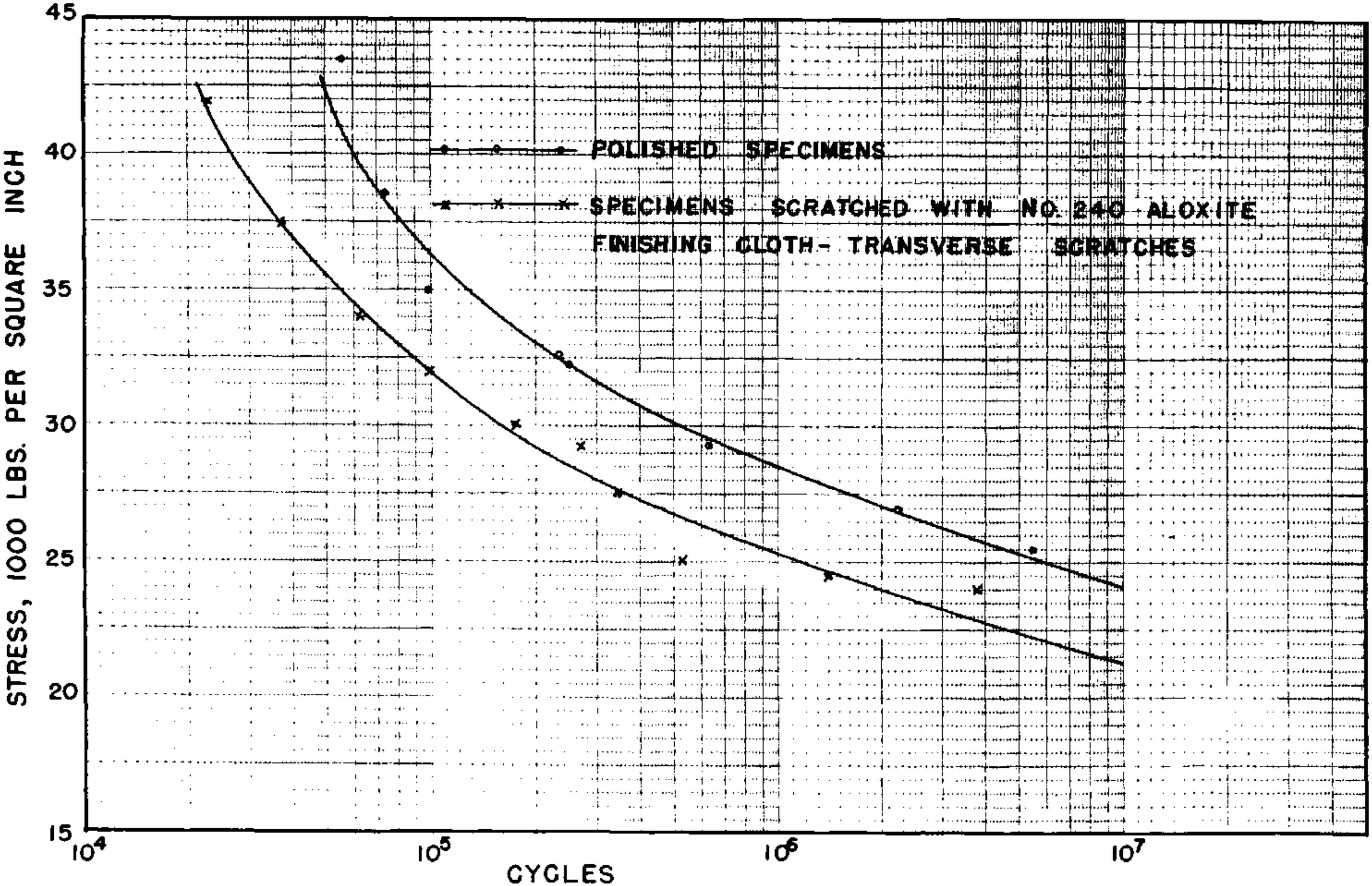

FIGURE 13. REPEATED FLEXURE FATIGUE

0.040 INCH 24 S-T SHEET

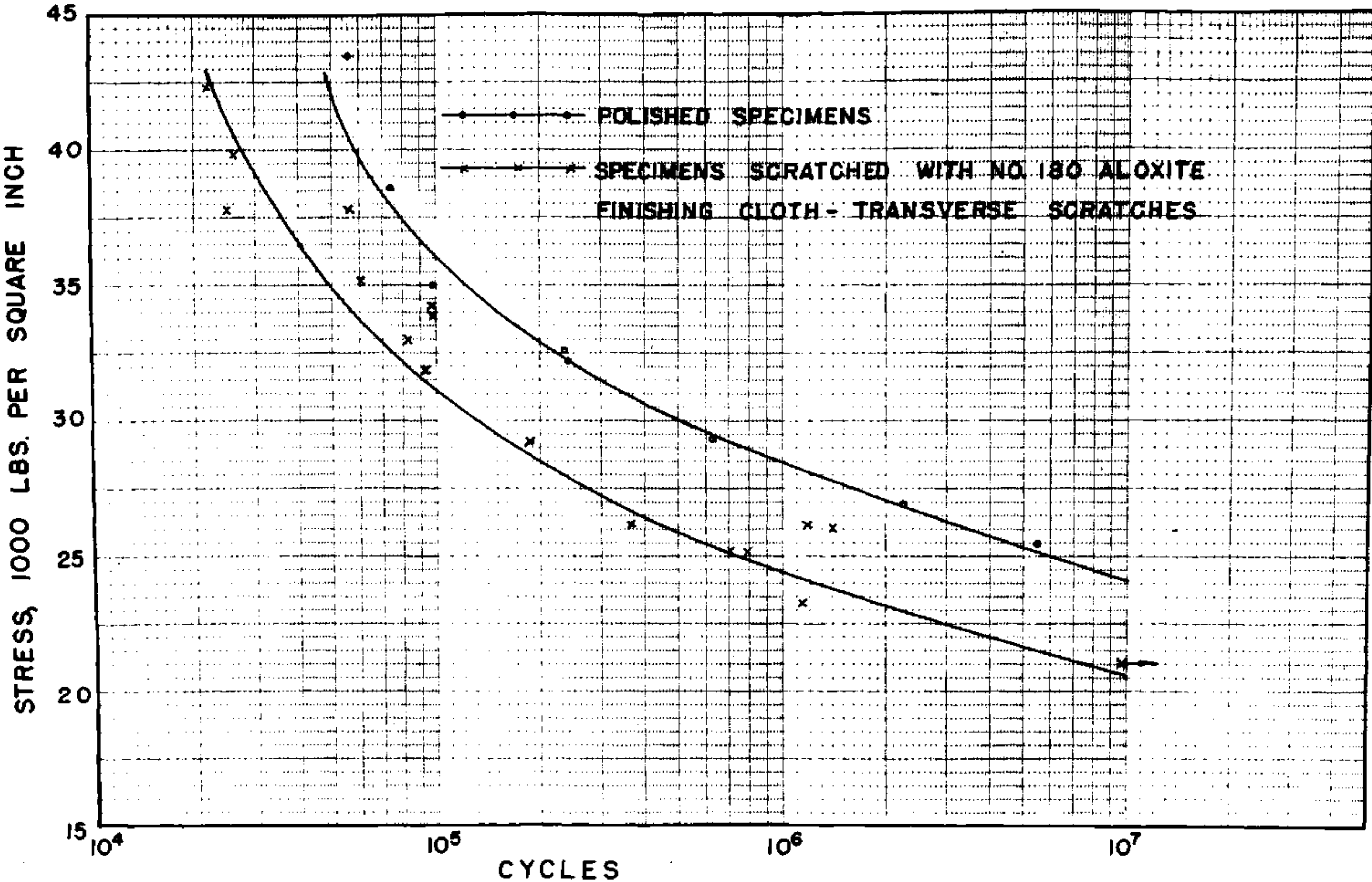

FIGURE 14. REPEATED FLEXURE FATIGUE

0.040 INCH 24 S-T SHEET

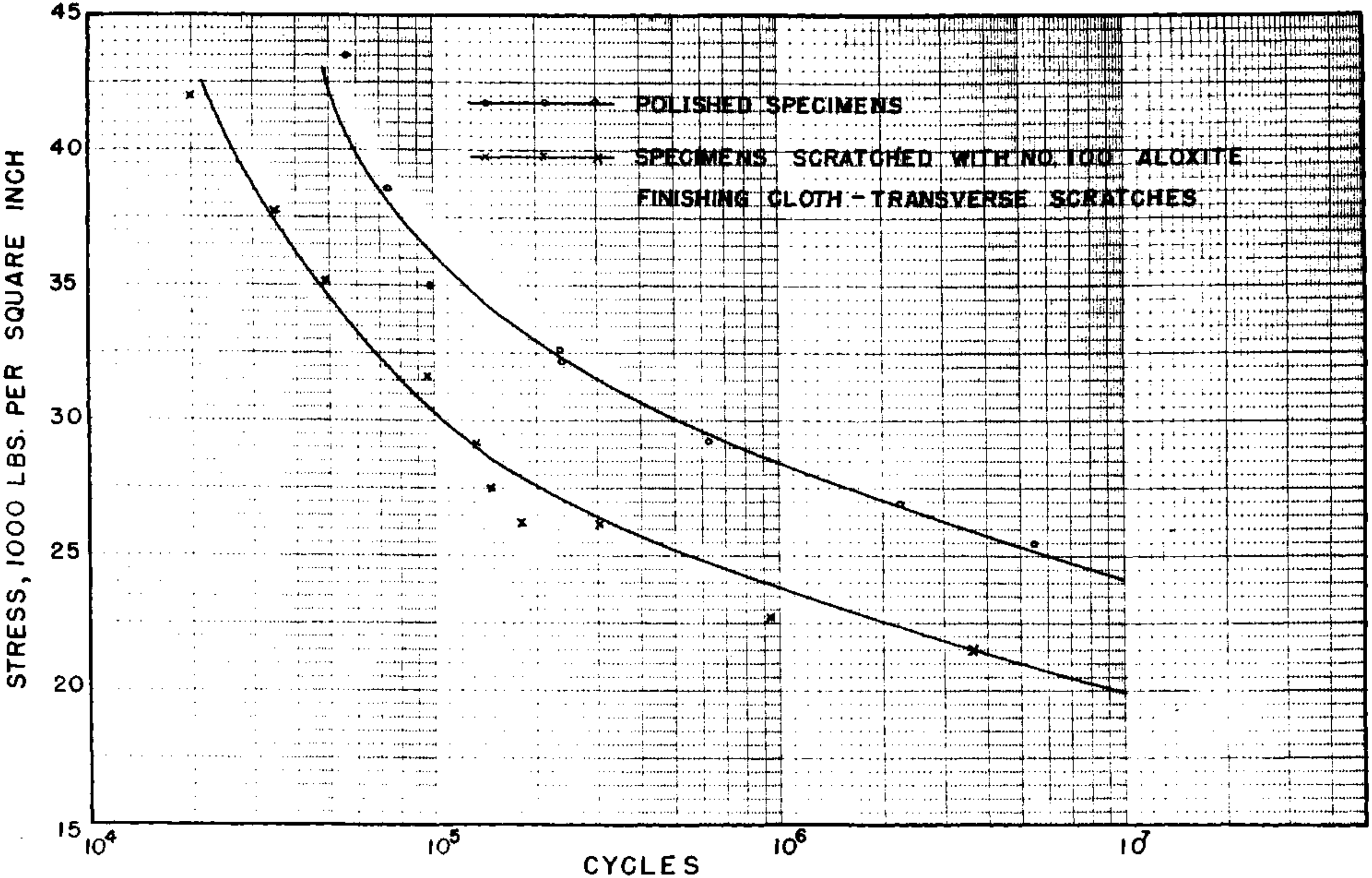

FIGURE 15. REPEATED FLEXURE FATIGUE

0.040 INCH 24 S-T SHEET

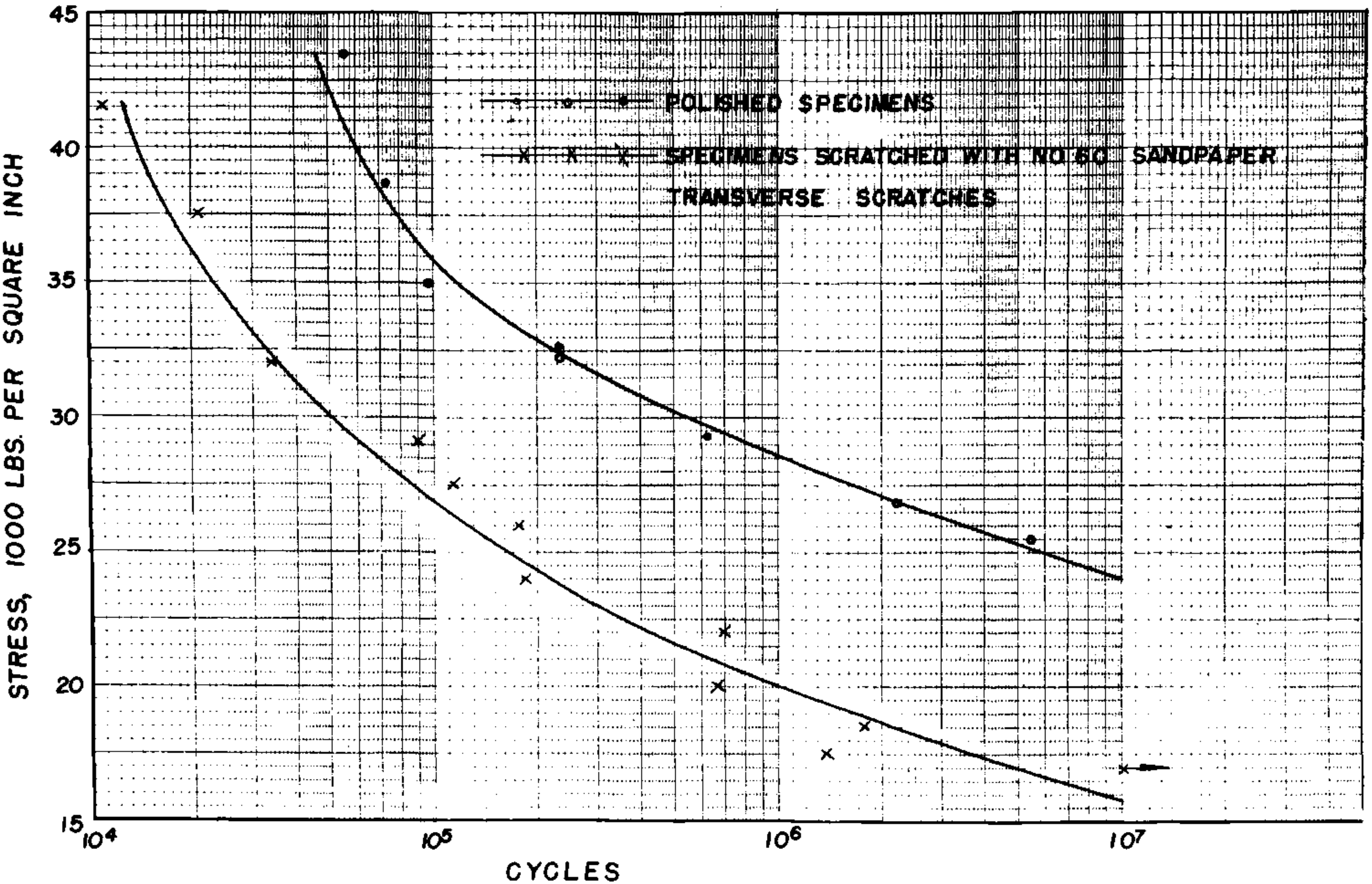

FIGURE 16. REPEATED FLEXURE FATIGUE

0.040 INCH 24S-T SHEET

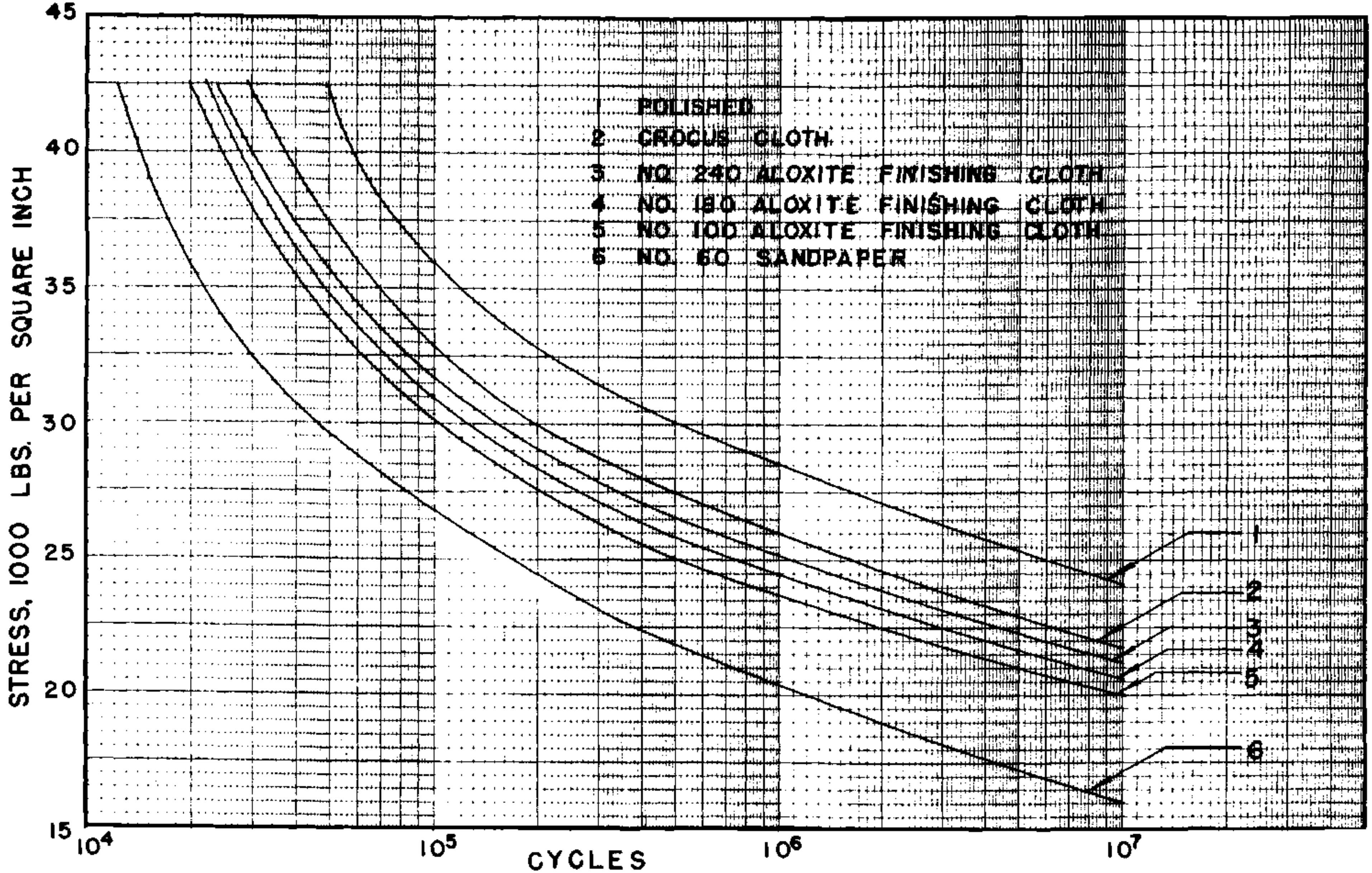

FIGURE 17. REPEATED FLEXURE FATIGUE CURVES SHOWING THE RELATIVE EFFECTS OF VARIOUS ABRASIVES ON THE FATIGUE LIFE OF 0.040 INCH 24S-T SHEET

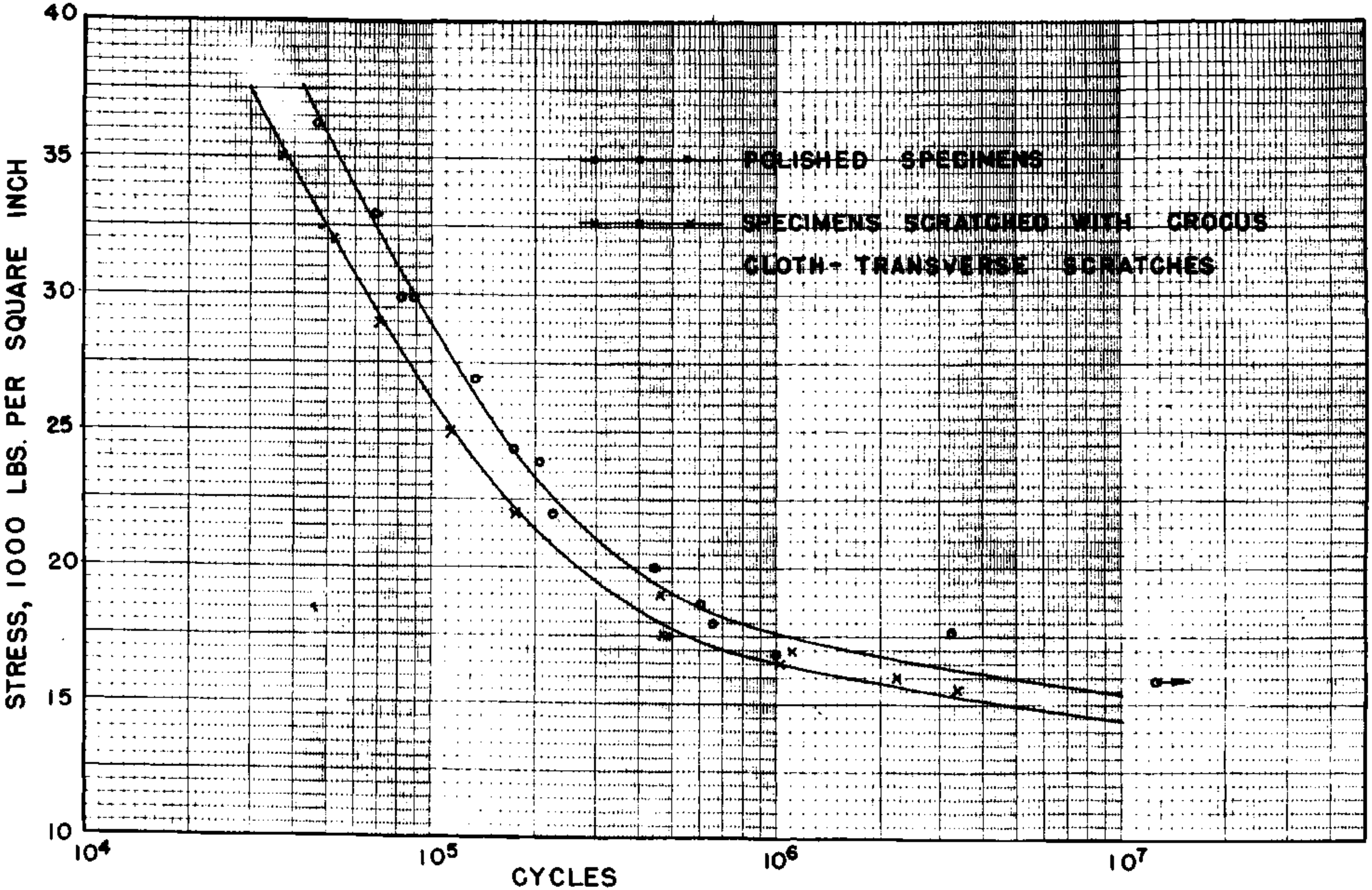

FIGURE 18. REPEATED FLEXURE FATIGUE

0.040 INCH 24 S-T ALCLAD SHEET

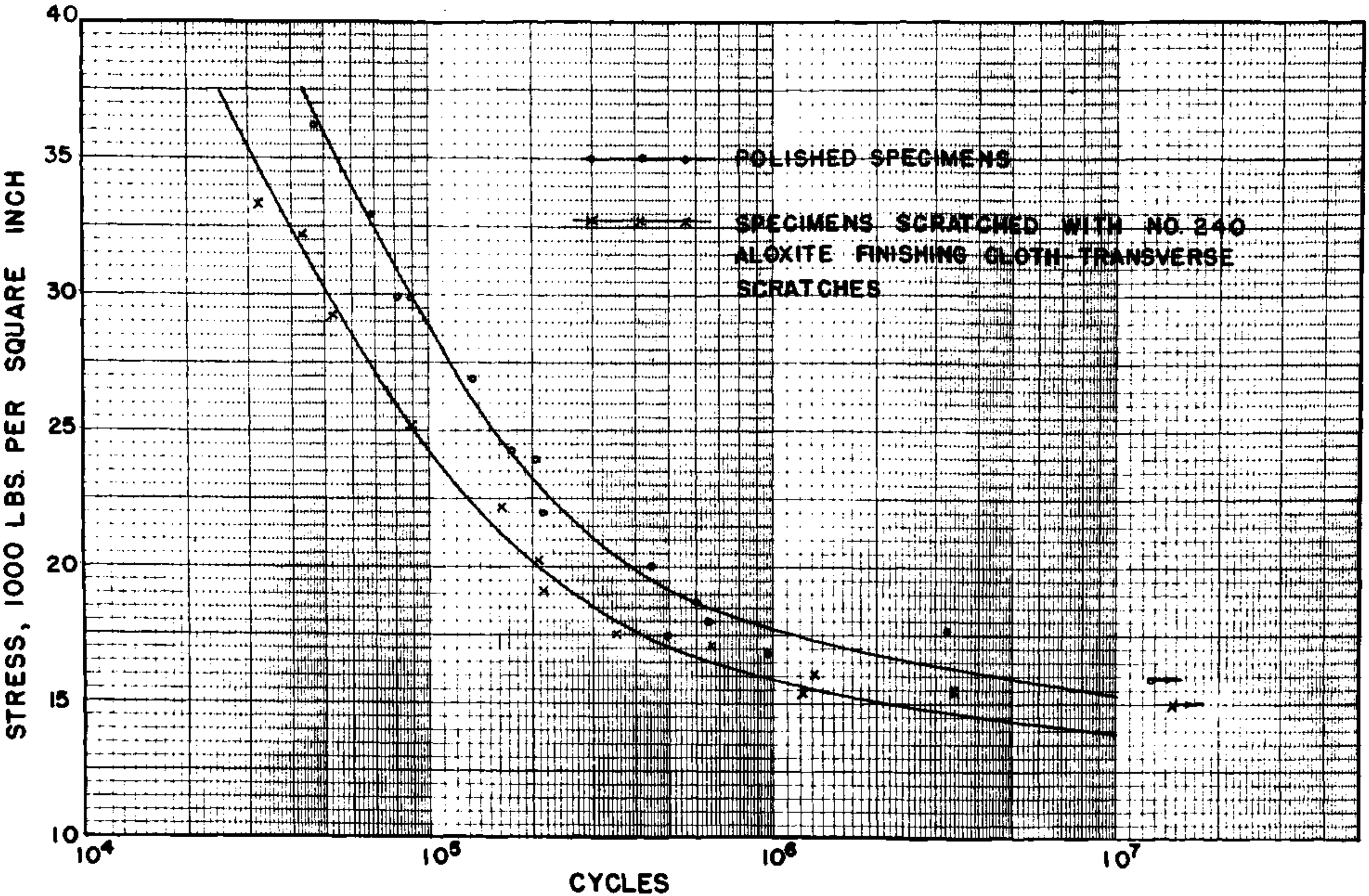

FIGURE 19. REPEATED FLEXURE FATIGUE
0.040 INCH 24 S-T ALCLAD SHEET

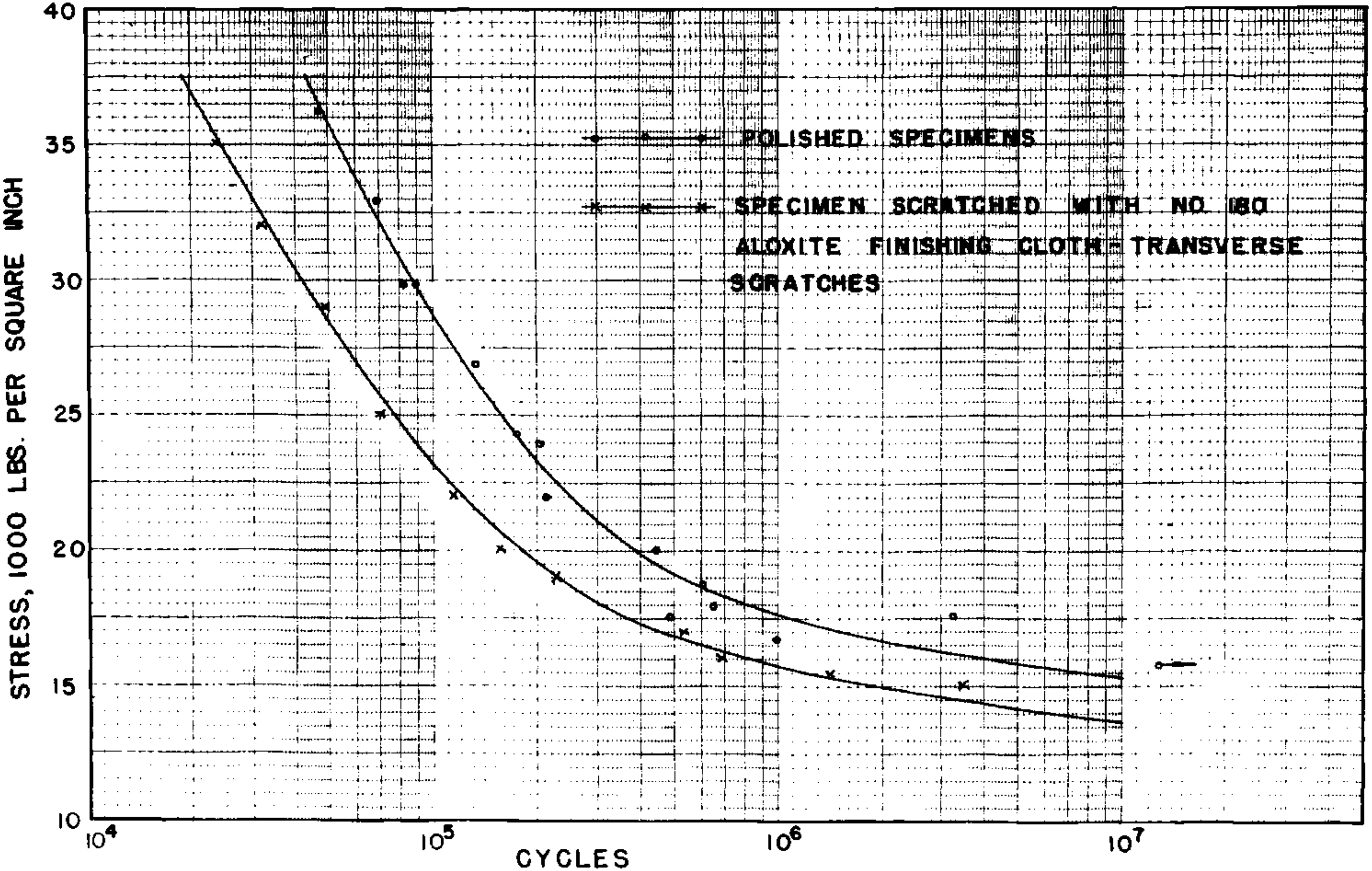

FIGURE 20. REPEATED FLEXURE FATIGUE

0.040 INCH 24S-T ALCLAD SHEET

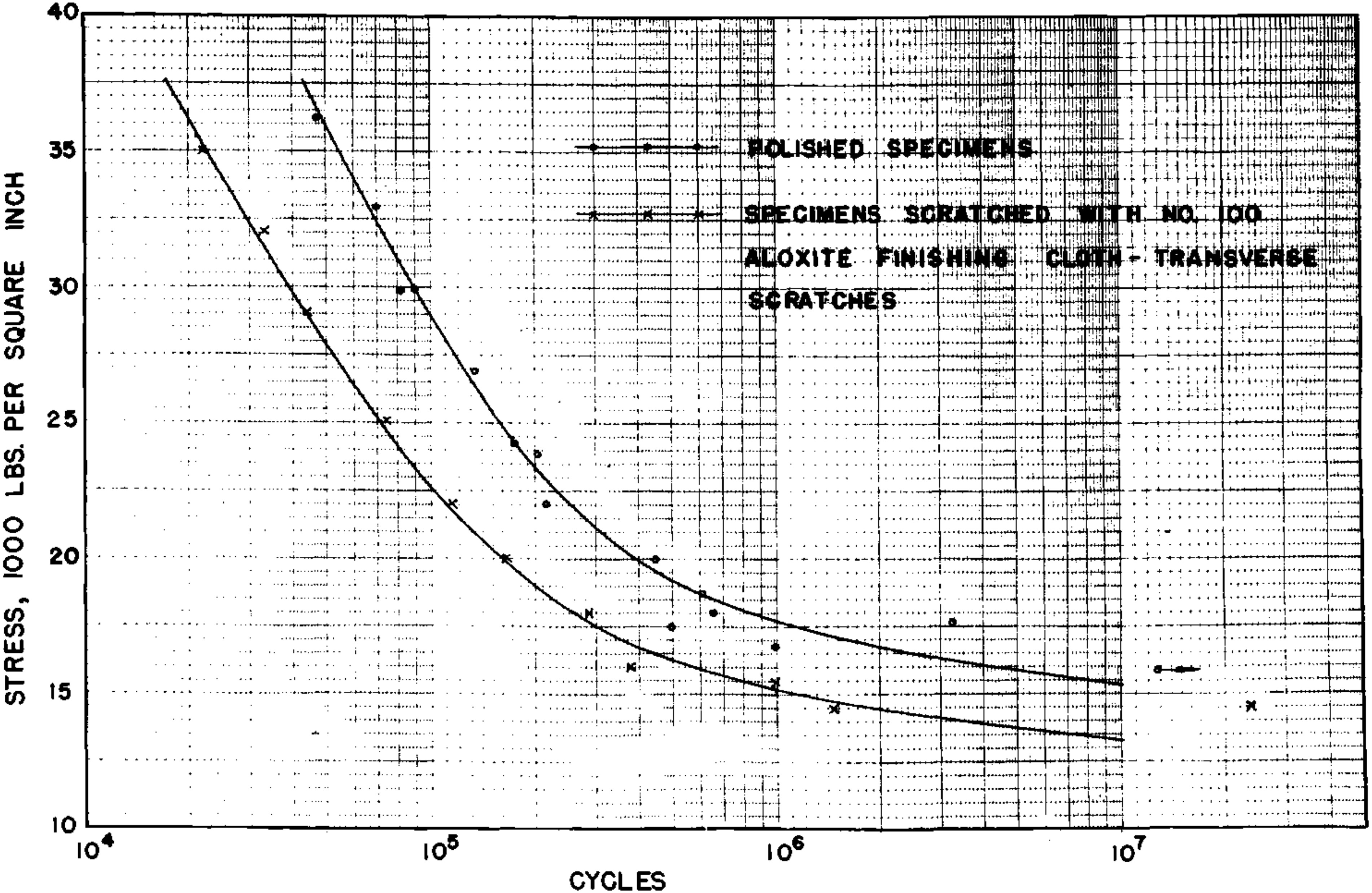

FIGURE 21. REPEATED FLEXURE FATIGUE

0.040 INCH 24 S-T ALCLAD SHEET

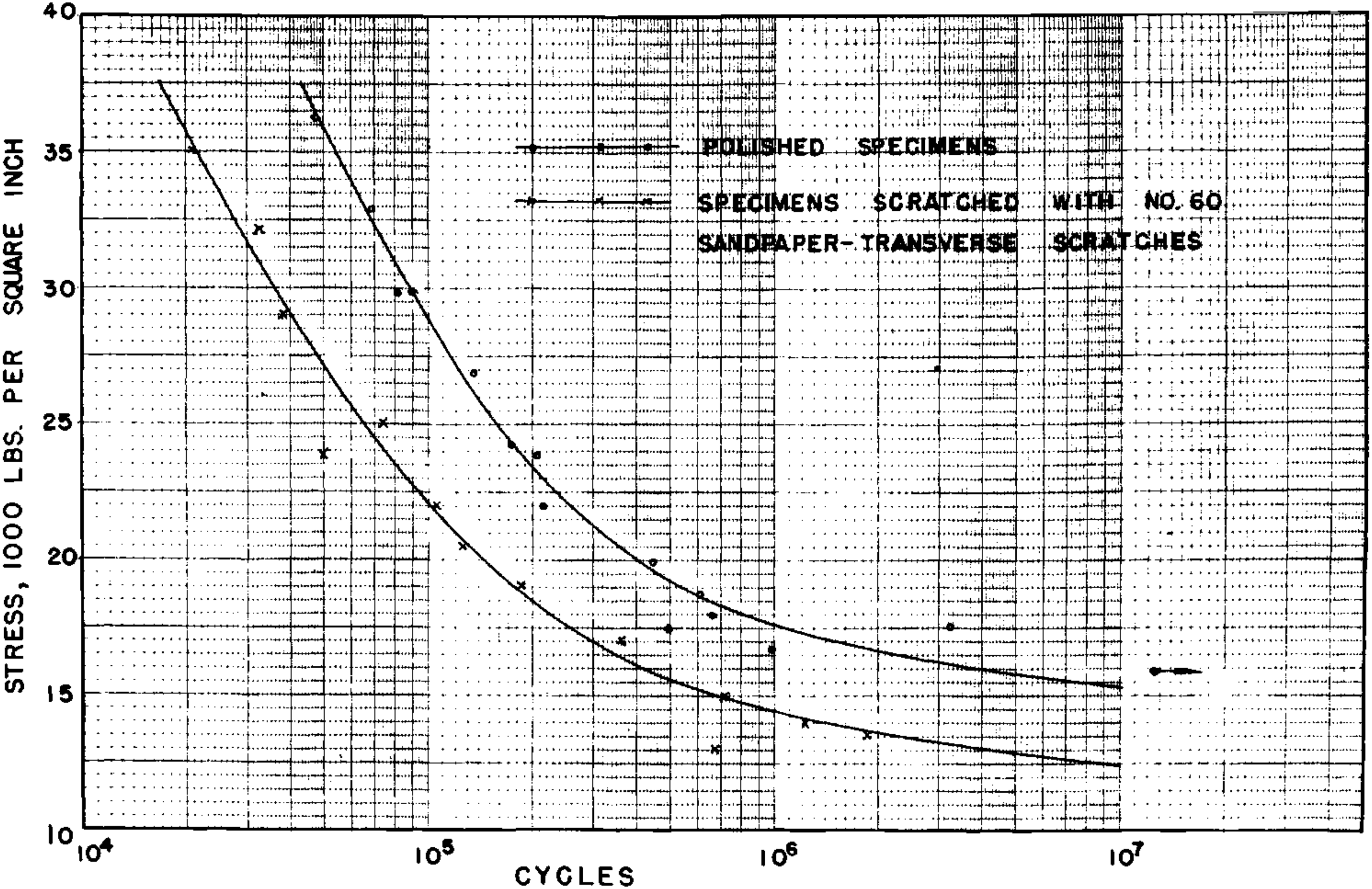

FIGURE 22. REPEATED FLEXURE FATIGUE

0.040 INCH 24S-T ALCLAD SHEET

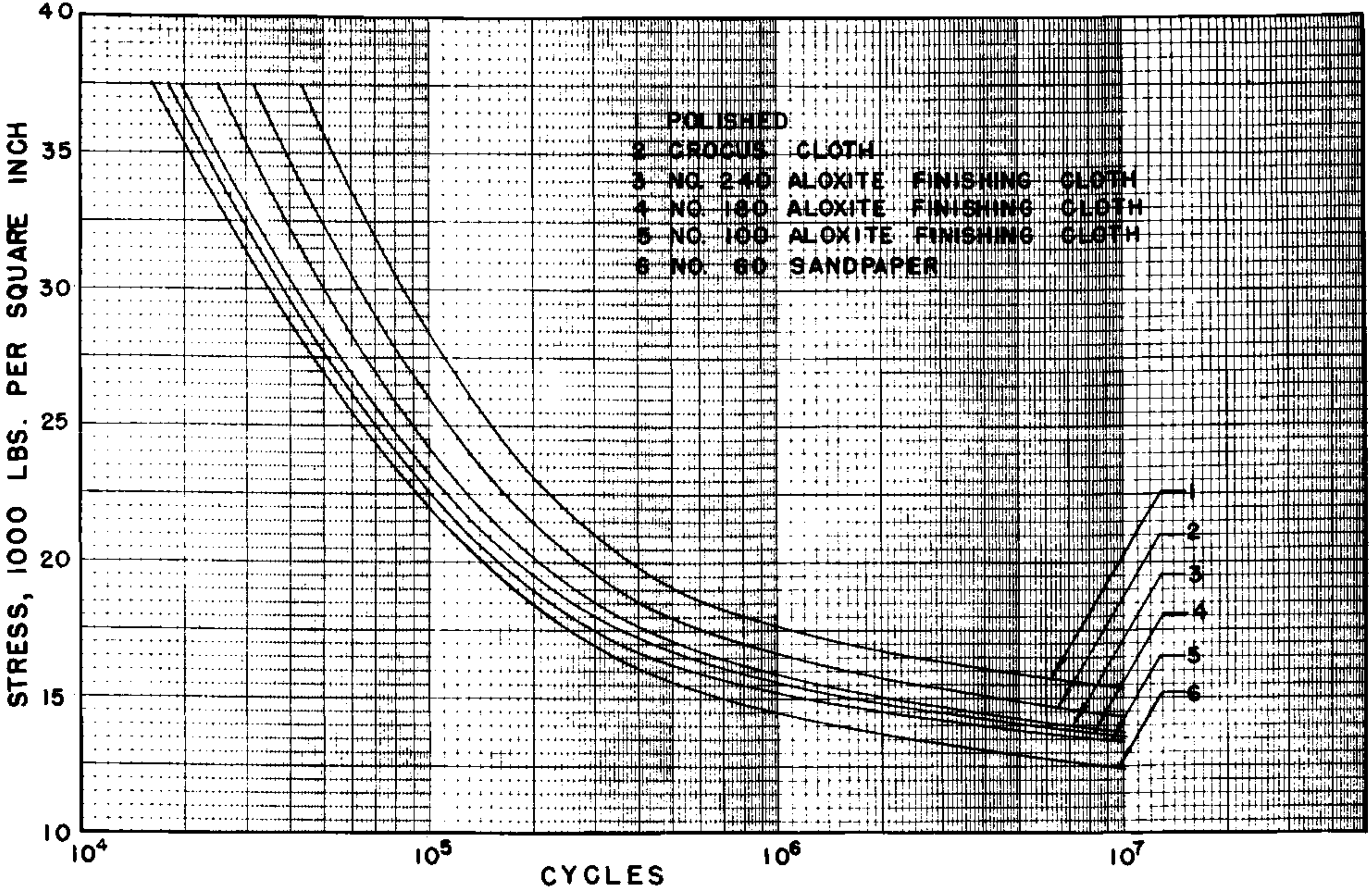

FIGURE 23. REPEATED FLEXURE FATIGUE CURVES SHOWING THE RELATIVE EFFECTS OF VARIOUS ABRASIVES ON THE FATIGUE LIFE OF 0.040 INCH 24S-T ALCLAD SHEET

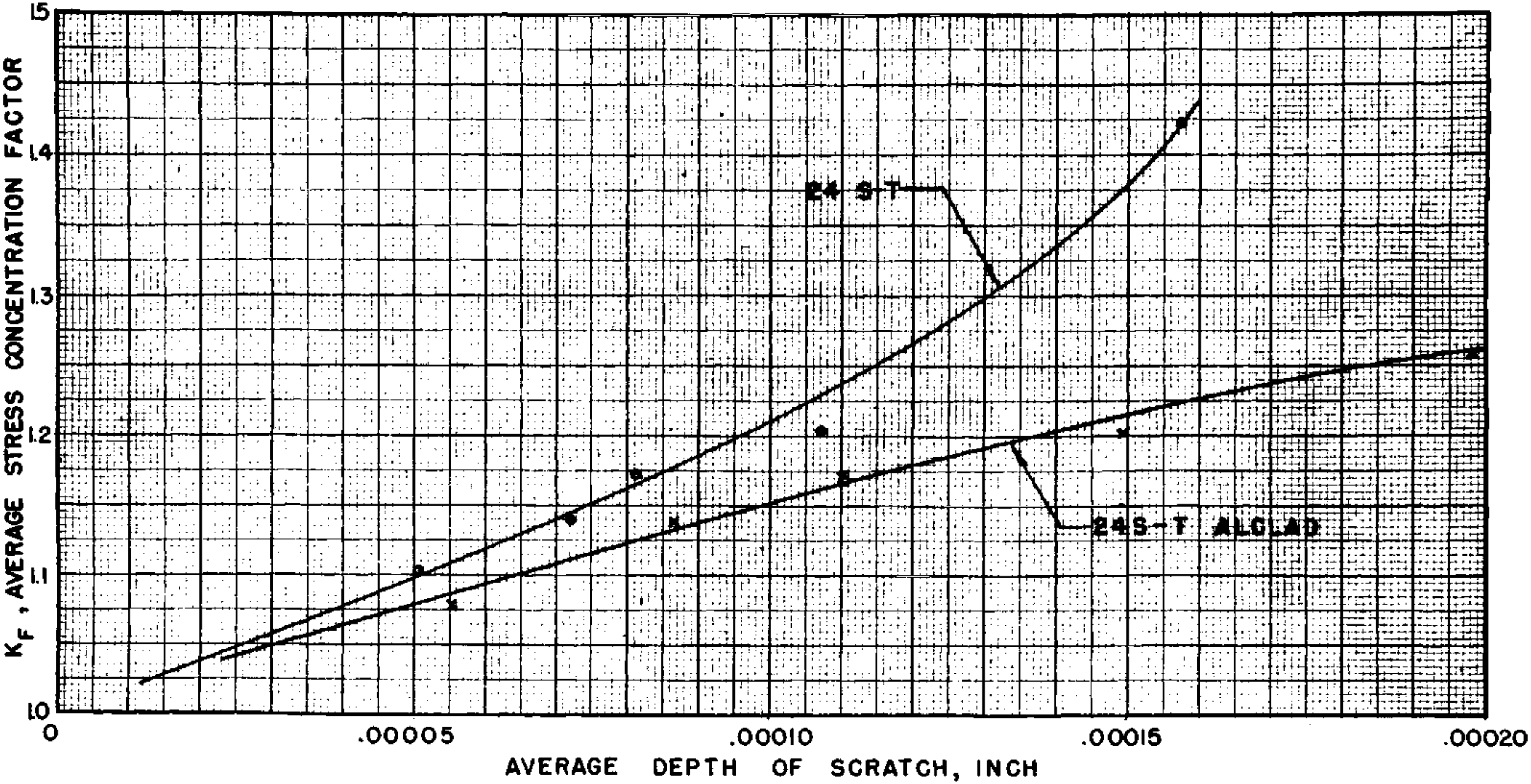

FIGURE 24. VARIATION OF AVERAGE STRESS CONCENTRATION FACTOR WITH AVERAGE DEPTH OF SURFACE SCRATCHES IN 0.040 INCH 24S-T AND 24S-TALCLAD SHEET IN REPEATED FLEXURE FATIGUE

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